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ACOUSTIC REFLEXES IN THE DECEREBRATE CAT

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In the course of some experiments undertaken with decerebrate preparations from the cat we noticed that not infrequently such preparations give evidence of reflex response to acoustic stimuli. Since fully similar observations do not appear, so far as we are aware, to have been recorded, we give here a brief account of the reactions as met in our experiments.

METHOD

Under profound anaesthesia induced by chloroform and ether inhalation, the cranial cavity was opened after ligation of both carotids. The dura mater was then incised freely and through the incision a spatula was inserted and with it a transverse severance made of the isthmus of the brain across the opening in the bony tentorium leading from the posterior to the middle fossa of the cranium. The whole brain in front of this section was then completely removed. There remained attached to the spinal cord the bulb and cerebellum with the posterior colliculi and usually some part of the anterior colliculi. How much of the anterior colliculi were left unremoved differed somewhat in the individual cases, sometimes the whole of them remained, more

commonly only their posterior half. During the performing of the severance and for a short time afterwards the vertebral arteries were compressed, restraining the haemorrhage until such time as clotting blocked the divided vessels. Keeping the head well raised above the trunk for a quarter of an hour after the removal of the brain was found also useful to control the haemorrhage.

After the decerebration, at various times during the course of other observations upon the preparation, the effect or non-effect of sounds on the reflex preparation was looked for. In all cases to which whistling was employed as a stimulus the animal was shielded from the blast of air, that no mechanical stimulus should confuse the issue. Since wholly negative results are of relatively little value we shall mention here only those results which were of a positive character. They were, shortly stated, as follows:

Experiment I, February 20, 1912. Decerebration completed at 12.10 p.m.

3.45. Clapping of the hands a few feet from right ear, the preparation lying on its left side, was followed regularly by brief contraction of the knee-extensor vasto-crureus, isolated and connected with the myograph.

4.35. Whistling and making a hissing sound 6 feet or less from head was followed regularly by brief contraction of the knee-extensor.

4.53. Retraction of the pinna as well as extension of the knee noted to follow the above stimuli.

5.19. Sharp hissing 3 feet from right ear caused in addition to contraction of knee-extensor and retraction of pinna a raising of the head, the head being carried to the right.

Experiment II, February 28, 1912. Decerebration completed at 10.35 a.m. Preparation on its right side. A long series of observations then followed on flexion reflex of left knee.

5.05. The note of a high-pitched Quincke whistle, also of whistling with the lips, was followed regularly by movement of left pinna.

5.30. An octave whistled from C upwards, with intervals of several seconds between notes, was followed regularly by the pinna-response for the upper half of its notes but not for the lower half. The pinna-response was elicited by Quincke whistles at 4 feet distance from head.

5.40. With repetition of the Quincke whistle at intervals of somewhat less than one second the pinna-response diminished steadily and ceased after seven seconds, but it returned after a short interval of rest.

Experiment III, March 1, 1912. Decerebration completed at 11.10 a.m. Preparation on right side.

1.30. Hissing or Quincke whistle evoked retraction of left pinna and slight turning of head to left. Right pinna did not move. Whistling on left side of head seemed more effective than whistling on right side; the response quickly tired.

1.47. The tip of the tail which hung sidewise over the edge of the table was moved to the right along with each pinna-response. The tail-reaction persisted after the pinna-response had ceased under frequent repetition of the whistle.

Experiment IV, March 5, 1912. Decerebration completed at 11.15 a.m. Spontaneous respiration did not appear till about 11.28 a.m., remained good after that for an hour or more. About 12.30 p.m. acoustic reflex was first noted. Hissing then evoked movement of pinna; reflex best obtained by hissing near left ear, the response, turning of head to left and slight movement of pinna. The response was obtained several times, but after about a minute the reflex disappeared and no response could be obtained.

At 1.10 decerebrate rigidity ceased in fore limbs and evidence suggestive of inadequate ventilation led to temporary use of artificial respiration.

1.43. Artificial respiration withdrawn. Spontaneous respiration vigorous, extensor rigidity pronounced.

2.05. Hissing again produced retraction of pinna. Respiration vigorous.

2.07. Respiration weaker, no acoustic reflex obtainable.

3.09. Movement of pinna again obtainable by hissing at some distance and by Quincke whistle.

3.42. Acoustic reflex still present.

4.12. Acoustic reflex not obtainable, nor was it at any time thereafter.

5.37. Animal was killed.

Experiment V, April 1, 1912. At 3.22, the usual decerebration having been completed four hours previously, transection of the anterior colliculi at their most posterior level was made with a sharp knife. This temporarily somewhat increased the existing extensor rigidity but excited no convulsion. No acoustic reflex could be obtained previous to the second transection.

3.25. Quincke whistle excited movement of pendant tip of tail.

3.29. The acoustic reflex had disappeared and could not again be obtained.

Experiment VI, June 28, 1913.[1] Decerebration completed at 11.15.

12.15. Preparation on its right side with tail overhanging table-edge. The sound of a metal pan struck with a stick caused the end of the tail to be raised to left with a quick twitch. The pan was about 20 feet from the preparation. The tail was moved thus each time the pan was struck.

12.33. Loud whistling evoked lashing of the tail-tip. Imitation of the yowling of a cat caused similar lashing of the tail-tip, and slight bristling of the hairs of the tail. The striking of one steel rod on another making a high-pitched note excited similar tail movement. A steel rod, whose pitch was above the audible range for human ear, was struck yielding to the latter merely the noise of a tap, but it caused in the preparation moderate lashing of the tail-tip. Wood struck similarly to produce the tapping sound as loudly as that from the high-pitch bar was not followed by any reaction on the part of the preparation. Whistling in imitation of a bird evoked lashing and bristling of tail. No movement of the pinna accompanied that of the tail.

2.20. Shrill whistling produced lashing of tail-tip.

Experiment VII, April 2, 1914. Decerebration completed at 10.35 a.m.

12.43. Clapping hands 6 feet from preparation evoked switching movement of tail. Hissing loudly at 15 feet from preparation and with face turned away from it caused switching of tail from side to side, not of whole tail but of last third.

2.35. A canary singing in cage about 15 feet from preparation caused switching movement of tail-end. This was repeated by covering bird-cage and uncovering it, and the reaction recurred regularly.

3.15. A dog barking loudly in the same room as the preparation excited the switching movement of the tail.

3.20. Imitation of the dog barking excited the tail movement, and this was repeated several times.

Experiment VIII, April 29, 1914. Decerebration completed at 10.50 a.m.

3.10. Shrill whistling evoked slight thrashing movement of end of tail but no pinna-movement. The sound of metals struck together

[1] This experiment was performed with the help of Dr. H. B. Williams at the College of Physicians and Surgeons, New York.

elicited more reaction, more effective still was imitation of the bark of a dog.

3.30. It was noted that flexion of right hip and slight movement of one forelimb accompanied the tail-reaction.

4.25. A low-toned barking sound evoked the reflex better than a somewhat louder noise made by beating on a tin.

Experiment IX, May 6, 1914. Decerebration completed at 11.13 a.m. At 12 noon, in response to a noise imitating barking of a dog, the preparation made a lashing movement with the tail, unaccompanied by any movement of pinna. Whistling evoked no response.

12.18. The movement of tail was evoked by whistling, but the imitation of barking evoked a more vigorous lashing of tail.

3.00. The reaction was elicited by a low-pitched shout more than 20 feet away.

It is noteworthy that in Experiment IV the acoustic reflex appeared and disappeared three times during the day, and that its disappearance seemed to be correlated with impairment of activity in the respiratory centre. In Experiment V the reflex was only present for about five minutes immediately following a second transection of the brain stem. Just what conditions are necessary for the response besides the intact reflex arc is not clear, but the above facts are suggestive in this connection.

As to further verification of the ablation of the brain in these experiments, the stump of midbrain with cerebellum and bulb was carefully removed post mortem. Examination showed that in the experiments the whole of the brain in front of the transection across the isthmus had been removed as indeed was obvious in the freely opened skull at the time of operation, the cranial cavity in front of bony tentorium being completely shelled out. In two of the experiments microscopic preparations were made of the part, the anterior colliculi, immediately behind the transection. The plane of the transection deviated little from the perpendicular to the long axis of the isthmus. The plane lay furthest forward in Experiment III, in which it lay a couple of millimeters in front of the anterior limit of the anterior colliculi—the exit of the third cranial nerves. It lay furthest back

in Experiment V, in which it lay a millimeter from the posterior edge of the anterior colliculi. In Experiment VII, its position was almost identical with that of Experiment V.

REMARKS

Observations on powers remaining to the central nervous system after mutilations of it divide themselves into two groups according as time has or has not been allowed for subsidence of diaschizis and other forms of shock and the possible restitutions of function. The observations reported here fall of course within the latter category. Regarding observations belonging to the former category it may be recalled that in Goltz's (1) dog, where the observations continued for eighteen months after removal of the cerebral hemispheres, the animal reacted to loud sounds by shaking its ears and could be wakened from sleep by the blare of a bicylcle horn close to its head. In this animal, however, parts of the basal ganglia and the sub-thalamic region remained (2). Recently similar experiments have been successfully carried out by Rothmann (3); reactions to acoustic stimuli were noticed. Small portions of the hemispheres remained and some of the substantia perforata anterior. Secondary atrophy had reduced very greatly the optic thalami. Roth's (4) observation on the goat, mentioned by V. Monakow (5), we have been unable to consult.

Karplus and Kreidl (6) have recently succeeded in obtaining observations on macaque monkeys subsequent to removal of both cerebral hemispheres. In one of their experiments the period of observation extended to twenty-five days from the time of ablation of the second hemisphere. Acoustic stimuli evoked movements of the pinnae, also of eyelids and eyeballs and drawing up of the body (Zusammenzucken des Korpers). Thus, (Monkey VII) their report notes on seventh and eighth days after removal of the second hemisphere "light noises evoked the ear-reflex, i.e., movements of both pinnae" in an animal in which post mortem examination, macroscopic and microscopic, showed that there remained nothing of the left hemisphere, and a 10 mm. fragment of right gyrus uncinatus. The striata and

thalami were also partly damaged; the corpus subthalamicum remained: The front part of the left anterior colliculus was also damaged. Again, in Monkey IX, in which there remained only traces of gyrus uncinatus and substantia perforata anterior, while caudatus, putamen and globus pallidus of striatum were destroyed except for part of pallidus on right side; the ventral part of thalami remained intact as also the geniculate bodies and colliculi. Of Monkey XV their note runs "greatly heightened reflex-excitability for acoustic and tactile stimuli, e.g., if another monkey in the animal-room utters a call the animal draws itself up violently (führt heftig zusammen)." In this case post mortem examination showed that on the right hemisphere a piece of gyrus uncinatus, and both right and left small pieces of orbital gyrus and fornicatus remained. Of striata the greater part remained intact, so also of the thalami. The colliculi and geniculata were practically intact.

In his experiments on the effect in the rabbit of removal of the brain in successive steps Christiani (7) noted that his operation of removal of hemispheres with the striata, but avoiding as far as possible injury to the optic thalami and parts further back was followed by heightened reactivity to stimuli especially of the acusticus. The animal was apt to pass into a condition resembling sleep from which it wakened with a start at a loud noise, the sound of a dog whistle or the striking of a match. The observations were made at longest a few hours after the operation.

Still more recently there has been the interesting case of the $3\frac{1}{2}$ years child examined by Edinger and Fischer (8). In this there was complete absence of cerebral hemispheres and thalami and partial absence of one corpus striatum, but the parts behind the thalamencephalon except for tracts proceeding from the hemispheres and thalami were practically intact. Of this child it was reported that a loud noise caused it to start but no reactions suggestive of actual hearing were ever observed although the mother had been at much pains to discover any such.

Comparing with these our own observations it is to be noted that in the latter the ablated fraction of the central nervous

system was somewhat larger than in the foregoing instances cited from the literature. In our experiments the ablated portion included as well as the cerebral hemispheres and striata the thalami, corpora geniculata and anterior portions of the anterior colliculi, also the whole base of the brain forward from a millimeter or so in front of the rootlets of the III cranial nerve-pair. Our examination of the reflex condition of the preparation was however entirely confined to the hours immediately succeeding the operative lesion. As to abeyance of function therefore our observations cannot discriminate between temporary (diaschitic) on the one hand and permanent (residual) defects on the other. But they are valid for supplying a minimal assessment of power still pertaining to the remainder of the nervous system left over after the ablation.

Acoustic stimuli evoked reactions from our preparations. The responses so evoked involved widely distant parts of the skeletal musculature. Retraction of the pinna, turning of the head, lashing of the tail, flexion and extension movements of the limbs, all these reactions were seen; sometimes they occurred together, sometimes apart.

As to the biological significance of these reactions the following inferences may, we think, be fairly drawn. The turning of the head and perhaps the movements of the pinna appear interpretable as orientation reflexes, i.e., reactions adjusting the organism in its relation to the spatual locus of the stimuli, and were the rest of the brain present, helping the organism to locate the sound.

The reaction of lashing of the tail-tip was in our experience one of the most persistent and characteristic of the responses. This mimetic movement is in the normal cat indicative of affective reaction. Darwin (9) describing the behaviour of a cat 'when threatened by a dog' wrote 'the whole tail or the tip alone is lashed or curled from side to side.' This lashing of the tail-tip was in our Experiment VI seen to be accompanied by bristling of the hairs of the tail, a phenomenon which supports the inference that the mimetic reflex was such as in the intact animal would have been attributive to emotion. The mimesis thus dis-

played may be taken as signifying aggression. MacDougall (10) links to the instinct of pugnacity the emotion of 'anger.' The character of the reflex mimesis in our experiments is further suggested by the efficiency of sounds resembling the barking of a dog, yowling of a cat, or the whistling of birds. It may be recalled that Goltz's dog (11) exhibited the mimesis of anger, although not that of any pleasurable emotion; and this was the case also in the experiments of Rothmann (12).

As exhibited in our experiments the mimesis was doubtless purely reflex. It was pseudoaffective in the sense employed by Woodworth (13) and one of us; that is, the mimesis although normally concomitant with the emotion of anger was in these experiments exhibited in absence of the emotion itself. There has been shown (14) to exist a nervous path, in the central nervous system, descending from the tegmental region of the posterior colliculus along bulb and lateral white columns of the cord which when faradised evokes lashing of the tail-tip and bristling of the tail hairs. This may be the path to which impulses excited by acoustic stimuli in the VIII nerves get access in the region of the posterior colliculi.

CONCLUSIONS

Certain acoustic stimuli excite reflex movements of the pinna, neck, tail and limbs in the cat even within a short time after complete removal of the cerebral hemispheres, striata, thalami, corpora geniculata and anterior portion of the anterior colliculi. The motor responses are of a kind which suggest that such stimuli can excite purely reflexly a certain amount of orientation of the animal to the stimuli.

Part of the reflex response in certain instances is of mimetic nature expressive of emotion of angry and aggressive character, though there is no reason to suppose that emotion or indeed any other truly conscious state attaches to the preparation.

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FARADIC STIMULI: A PHYSICAL AND PHYSIOLOGICAL STUDY

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TOPICAL OUTLINE[1]

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PART I—APPARATUS AND METHODS IN GENERAL
- Description of coils
- Description of apparatus
- Proportionality of the deflections of the string galvanometer
- Interpretation of records of the string galvanometer

PART II—SINGLE INDUCTION SHOCKS
- Configuration and duration of induction shocks
- Relation of the contour of shocks to their value as stimuli
- Foreshortened shocks
  - Effect of foreshortening on configuration
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- Aftershortened shocks
- Effect of strength of shocks on their configuration and stimulating value
- Secondary resistance
  - Effect on configuration
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- Discussion of the relation of data to the physical calibration of induction coils

PART III—REPEATED SHOCKS
- Make-break couples.
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  - Interchange of effectiveness of make and break shocks
- Break-make couples
- Discussion
- Tetanic stimulation
  - Effect of rate of interruption on stimulating value of shocks
  - Effect of "short-circuiting" the make shocks
  - Initial contractions

Summary

[1] This topical outline is abbreviated from the outline consisting of the headings in the text.

INTRODUCTION

The study of induction shocks recorded in this paper was suggested by certain results obtained by one of us during the course of some experiments devised for the purpose of gathering information relative to a theory of cardiac inhibition put forward tentatively some time ago. In these experiments a strip of turtle's ventricle was stimulated through and through with shocks from an induction coil (coil 1) of the du Bois-Reymond type. The primary circuit was interrupted and *the make shocks were short-circuited* by means of a modified Ludwig-Hüfler interrupter made by Zimmerman. It was found that, as the rate of stimulation increased beyond a certain point, the rate of the contractions of the strip decreased, the strip finally failing altogether to respond to the stimuli after passing through a stage in which only an initial contraction was obtained. More specifically the results were as follows: When the break shocks were applied at the rate of approximately 33 per second the contractions of the strip were at the rate of one per three seconds throughout the period of stimulation; shocks at the rate of approximately 38 per second gave only two initial contractions, again at the rate of one per three seconds; stimulation at the rate of 80 breaks per second gave only one initial contraction; while shocks supplied at the rate of 100 per second failed altogether to stimulate.[2] Although these results seemed to substantiate the theory of inhibition, at least in part, it was nevertheless deemed advisable, before putting this interpretation on the results, to assure ourselves of the trustworthiness of the apparatus employed.

To this end a rough preliminary investigation of the induc-

[2] In this preliminary experiment the rate of interruption was determined by counting out the number of shocks delivered while the friction wheel of the interrupter was at 60 on the scale and then, upon the assumption that the rate of interruption is doubled when the distance on the friction disc is halved, a curve was constructed and the intermediate rates determined therefrom by interpolation. In all subsequent experiments, excepting where a specific statement to the contrary occurs, the rate of stimulation has been accurately determined.

tion shocks was made by transferring the terminals of the coil (No. 1) from the heart muscle to a delicate d'Arsonval galvanometer, and then repeating the experiment as it had been performed with the muscle. It was found that at first, in accordance with expectation, the deflection of the galvanometer increased with the rate of interruption.[3] We were surprised to find, however, that beyond a certain rate of interruption the increments of the deflection with increasing rate of shocks became smaller and smaller and then negative, the spot of light eventually passing back to, and then to the other side of, the zero

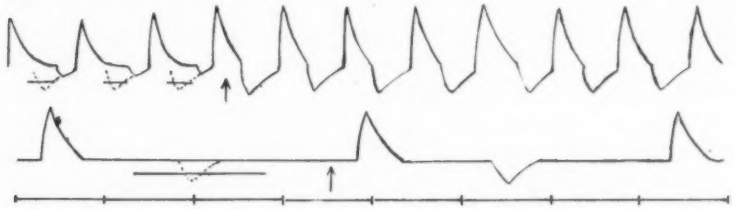


Fig. 1. Reconstruction from a record to show the escape of a part of the make shock beyond a short circuit when the rate of interruption is increased. The short circuit was operating in both records, upper and lower, in the parts preceding the arrows and during the periods indicated by the straight lines drawn below the records. The make shocks eliminated by the short circuit are indicated by the dotted lines. The time is indicated in tenths of seconds. In this record and in all that follow, deflections above the zero line are produced by break shocks, those below by make shocks.

point. This curious result seemed explicable only upon the assumption that with the more rapid rates of interruption currents opposite in direction to those of the break shocks assumed the ascendency. A trial experiment in which the string galvanometer was substituted for the ballistic galvanometer, confirmed this assumption: with the slower rates of interruption the deflections (breaks presumably, since the makes were being short-circuited) were in one direction only (fig. 1, lower curve); with the more rapid rates, however, additional deflections in the

[3] The ballistic galvanometer gave, with the rapid rates of interruption employed, a deflection that was practically steady.

opposite direction appeared (fig. 1, upper curve) the amplitude of these new deflections increasing with further increase in the rate of interruption.

While it was obvious that this result could be explained only by assuming that with the more rapid rates of interruption the make shocks were outlasting the period of the short circuit, and that the residue of the make shock left in the coil after the termination of the short circuit was flowing through the main circuit, it was nevertheless realized that such an assumption was not in consonance with the generally accepted conception as to the duration of shocks yielded by induction coils in current use by physiologists. It was from such considerations as these that the present investigation has grown. The results we have obtained fully confirm the premises.

It should be made clear at the outset that our problem does not concern itself primarily with an attempt to determine the specific value of faradic stimuli, or to calibrate induction coils; neither was it planned originally to study the form of induction shocks, nor the relation of form and duration of shocks to physiological response. Rather, we planned to adhere as closely as possible to the phases of the subject that had led us into it; namely, an effort to determine the effect upon the physiological value of shocks of procedures commonly employed in the physiological laboratory. Yet we have found it necessary, in order to gain facts relative to our main thesis, to enter to a certain extent into other phases of the subject, including some of those mentioned above. And while at many points our problem has brought us face to face with questions involving in their consideration the fundamental physical principles of the induction coil, in the present investigation we purposely have entered into the physical aspects of the subject only so far as has seemed necessary to attain the end in view.

PART I. APPARATUS AND METHODS IN GENERAL

Description of coils. In the course of the observations herein recorded, three induction coils, hereinafter designated coils 1, 2 and 3, have been studied. They were of the usual physiological types and were not provided with condensers. Their construction is described as completely as is possible in the absence of detailed information, in Table I.

Coils 1 and 3 were of the vertical type.[4] Coil 2 was a horizontal coil designed by Porter (2). The core of coil 1 was fixed, that of 2 removable, but with considerable difficulty, while that

TABLE I

Description of coils

	COIL 1		COIL 2		COIL 3	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
Length of coil in mm.*	115.00	115.00	66.00	65.00	120.00	116.00
Diameter of coil in mm.* inside	19.00?	47.00	13.00	24.00	24.00	39.00
Diameter of coil in mm.* outside	33.00	75.00	21.00	38.00	34.00	65.00
Number of windings	?	5000.00	?	5000.00	?	10,000.00
Diameter of wire in mm.*	1.30	0.46	0.82	0.2	1.02	0.23
Number of layers	?	?	?	?	?	?
Resistance in ohms*	0.48	180.00	0.55	290.00	0.90	1100.00

* Measured by us; other data from manufacturers' description.

of 3 could be conveniently withdrawn. The coils seemed to be well constructed; they were all carefully examined with the possibility of short circuits in view, but no evidence of such a defect was discovered.

Primary current. In the earlier experiments two Type S, Edison-Lelande cells, in series, were used to supply the current. After these had been in use for some time it was found that the amount of current yielded by them fell off perceptibly during even short closures of the circuit. These cells were then replaced for the most part by one Daniell cell, which was found to be

[4] Obtained through Baird and Tatlock, London.

quite dependable. The amount of current passing through the primary circuit was indicated by an ammeter graduated in hundredths. This meter, at the same time, served as a check upon the connections in the primary circuit. The current indicated by the ammeter, of course, depended upon the resistance of the coil used and upon the resistance of the connections in circuit with it. Although the latter were changed from time to time for experimental purposes, the ammeter usually indicated a current of from 0.75 to 1.00 ampere. When, in comparative experiments, it was necessary to keep the amount of current constant, the resistance in the primary circuit was usually adjusted to let through 0.50 ampere.

Interrupters. Various devices have been used for the purpose of interrupting the primary circuit and of short-circuiting the secondary circuit, or the galvanometer circuit.

The first interrupter employed, as has been said, was one of the Ludwig-Hüfler type. With this interrupter the break of the primary circuit is accomplished by the sliding of a steel spring into notches on the periphery of a rotating brass disc, the current being reëstablished by contact between the spring and the brass disc at the end of the notch. This interrupter we have designated the *notched rotary interrupter*. From time to time, in the course of our work, the rotary interrupter was materially modified for the purpose of adapting it to special needs. The most important modification consisted in replacing the notched brass discs by brass discs with fiber segments of various sizes, the whole turned down so as to offer to the contact springs a smooth circumference. In this way the makes and breaks could be more readily compared, and at the same time it became possible, when the rate of rotation was known, to measure the time intervals accurately on the circumference of the disc. This was impossible with the unmodified instrument because of the bending of the contact springs into and out of the notches. The rotary instrument thus modified will be designated the *smooth rotary interrupter*. As has been indicated, the rotary interrupter could be driven at a known speed, and the speed frequently selected has been such that 1 mm. on the

circumference of the disc equaled 1.0 σ.[5] It thus was possible, by rotating the discs on each other through known distances, to arrange for any desired time interval between shocks, between shocks and short circuits, etc.

We found it very difficult to obtain a perfectly steady contact with this interrupter; even when the discs were highly polished the galvanometer connected with the secondary coil practically always showed, while the discs were rotating, slight deflections during the periods the primary circuit was closed. These irregularities interfered somewhat with the determination of the duration of the make shocks and caused some variation in the amplitude of deflection of both the make and break shocks. When the investigation was almost completed it was discovered that an absolutely steady current could be obtained by lightly amal-

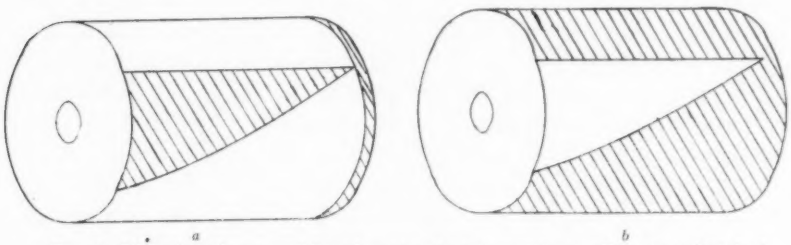


Fig. 2. Make-break (*a*) and break-make (*b*) interrupters. The cross-hatched areas represent conducting material. The plain areas, nonconducting material.

gamating the brass discs of the interrupter. All excess of mercury was removed in order to avoid the danger of any accumulation under the brushes.

For certain experiments requiring a nice gradation of the time interval between makes and breaks, or breaks and makes, cylinders with a V-shaped surface of conducting or of non-conducting material, respectively, and termed hereinafter the *make-break* or the *break-make interrupter*, and of the construction shown in figure 2, replaced one of the cylinders of the rotary interrupter. With this device the shock intervals could be very conveniently

[5] 1 σ = 0.001 second.

and accurately varied without varying the speed of rotation, by sliding one of the contact springs over the cylinder parallel to its axis of rotation.

Use was also made of a *Helmholtz pendulum* built in this laboratory. The pendulum finally employed was adjusted to move in the vicinity of the keys with a velocity of 16.5 mm. per 10.0 σ. In its path were two, in some experiments, three, platinum contact, knockover keys separated by distances that could be varied by means of coarse and fine adjustments. With this instrument time intervals could be obtained that were accurate to 0.2 σ.

With the Helmholtz pendulum it is difficult to obtain through platinum keys make contacts that are free of shatter. A key for this purpose has been described by Gildemeister and Weiss (3). We also have devised a *make key* for use with the Helmholtz pendulum and have found by controls made with the aid of the string galvanometer that, when properly adjusted, it yields perfectly pure make shocks. The principle of this key is indicated in figure 3. A rigid bar pivoted at *A* is carried by the pendulum from position 1 in the direction of the arrow to position 2. In this way the contact is established at *B*. Shattering is completely eliminated by the slipping of the pall, *C*, into the notch, *D*. This takes place practically at the instant the contact is established at *B*. The hardened steel angles of the pall and notch are very true, and are inclined so that the motion inward of the pall is accomplished with but very slight further rotation of the bar, *A*, on its axis. The key is adjusted by setting the contact screw, *B*, so that, when it touches the post, *F*, the pall, *C*, has moved only a part of the way into the notch, *D*. The pendulum is permitted to pursue its way after the contact has been established, by flexing before it the hinged end, *E*, of the bar, *A*. In position 1, the two limbs of the bar are held firmly in the extended position by the spring, *G*. Inasmuch as the key moves freely around the pivot, *A*, the spring, *G*, prevents any flexion of *E* until the metal parts meet at *B*. After the pendulum has swung past the key, the spring, *G*, by virtue of the direction of its pull, holds the two parts of the bar in flexion.

Martin's mercury key (4) has also been used. The shocks yielded by this key, as recorded with the string galvanometer, often have been most irregular. These irregularities, we believe, are due in some way to eddies set up in the mercury by the quickly moving vane. However this may be, it has been found that the records become more regular when by means of friction

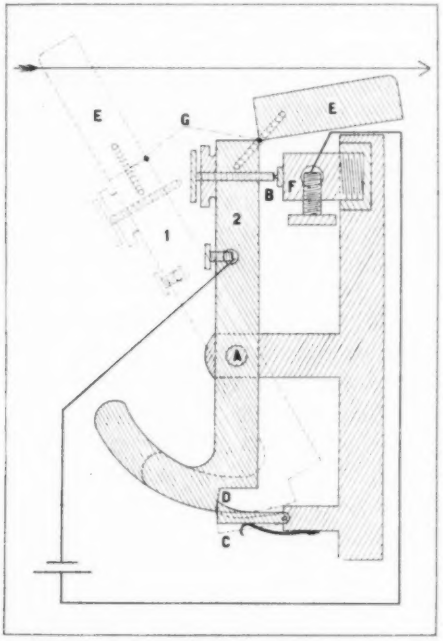


Fig. 3. Make key. Description in text.

the velocity of the vane is decreased. Then, however, there may be some risk of establishing the contacts so gradually as to affect the process of induction.

Galvanometers and physiological preparations. In the study of the manifestations of induction shocks we have used (a) the ballistic galvanometer, (b) the string galvanometer, and (c) certain physiological preparations.

(*a*) The ballistic galvanometer employed was of the Rowland-d'Arsonval type.[6] In most of the experiments this galvanometer was connected in series with the secondary coil.

(*b*) The string galvanometer employed was of the large Edelmann type. During the entire investigation three strings have been used, two of platinum with resistances of 4400 ohms and 9700 ohms, respectively; the other of silvered quartz with a resistance of 6000 ohms. Low resistance strings have usually been employed because the resistance of the galvanometer circuit was usually relatively low. A high degree of sensitiveness was not required since it was always necessary to shunt out of the galvanometer most of the current developed in the secondary circuit. Quickness of movement was a far more important requisite (see page 391). For this reason the string has always been stretched as tightly as seemed safe. The deflection produced at a distance of one meter by one millivolt was usually between 2 and 3 mm.[7]

(*c*) The physiological tests were made with the frog's gastrocnemius muscle stimulated usually directly, occasionally indirectly through its nerve, and with the turtle's heart. The current was applied to the gastrocnemius muscle by the method, described by Martin, of piercing the muscle with needle electrodes of platinum. The method proved thoroughly satisfactory, though we found it necessary, as has Martin also, to take into account the direction of the current through the preparation; otherwise the polar effects, which may be quite marked, due to unequal densities at the two ends of the muscle, would have vitiated comparative estimations. In the few experiments in which the muscle was stimulated through its nerve, the usual platinum electrodes were employed. The shortening of the muscle was registered by a light but rigid lever moving before the slit of the photographic registering apparatus. The lever was not after-loaded, and carried close to its fulcrum a weight of about 10 grams. In some experiments the contractions of the

[6] The type P instrument of the Leeds-Northup Company.

[7] Zeiss apochromatic objective, 4 mm., and projection ocular 2, at a distance of one meter.

muscle were recorded on smoked paper while the deflection of the string, if this information was also desired, was read in the mutostat.[8]

Arrangement of connections. The arrangement of the connections joining together this apparatus, was, of course, frequently changed to suit special needs. The arrangement most frequently employed[9] is shown diagrammatically in figure 4.

In the primary circuit are shown the battery, B, the primary coil, P, the key, K_1, for throwing the ammeter, A, into or out of the circuit, the resistance, R_1, for regulating the amount of current, the interrupter, K_2, of the interrupting and short-circuiting apparatus, and the electro-magnetic signal, E. In the secondary

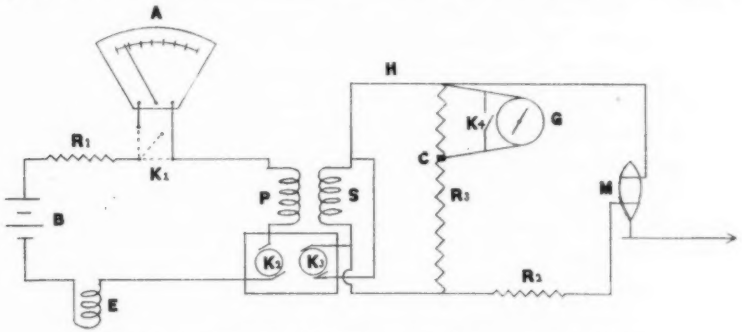


Fig. 4. Arrangement of connections. Description in text.

circuit may be seen the secondary coil, S, the key, K_3, of the interrupting and short-circuiting apparatus, used usually as a short circuiting key, excepting where specific statement to the contrary occurs, the muscle, M, the resistance, R_2, in series with the muscle, the shunt resistance, R_3, usually of 3277 ohms, the string galvanometer, G, so connected with the resistance, R_3, by means of the sliding contact, C, that a known and usually very small fraction of the secondary current could be led through

[8] We have designated by the term "mutostat," the "cylindrical lens wheel" attachment to the Edelmann photo-registering apparatus, which is used to view the curve of the actuated string as it will appear on the photographic record.

[9] Other arrangements will be mentioned in connection with the topics in the investigation of which they were used.

the galvanometer, and the key, K_4, for short-circuiting the galvanometer. It might be mentioned here that, inasmuch as the fraction of the current used for the galvanometer was always very small, rarely exceeding 1 per cent of the whole and never, when this arrangement was employed, exceeding 4 per cent, the effect of the position of the key, K_4, whether open or closed, upon the response of the muscle was usually negligible. So as not to complicate the diagram, only the important keys and connections are shown. Two keys are omitted that were used to quickly and conveniently establish the Helmholtz arrangement for equalizing the make and break shocks; also the keys for short-circuiting the secondary coil, for throwing the secondary circuit in series into the d'Arsonval instead of into the string galvanometer, for shifting quickly from one to another of the induction coils, for reversing the current in any of the circuits including the galvanometer circuit, etc. The connections employed in calibrating the galvanometer have also been omitted.

Precautions against outside induction. Precautions were taken to prevent induction from and by outside coils and wires, and controls have been made with circuits containing no coiled wire whatever, excepting that of the induction coil itself. The results of these controls differ in no perceptible manner from the general results. The resistances were all of the non-inductive type. When comparative observations were being made upon two coils simultaneously, the coils were placed at right angles to each other. It might be added that in many of the experiments a signal magnet, E, the bobbin of which consisted of relatively few turns of heavy wire, was kept in the primary circuit. This was done partly because it is a very common arrangement of the primary circuit in physiological experimentation. The armature of this magnet naturally moved more slowly than the string. Where this lag is sufficiently great the records show that the movement of the armature perceptibly, though immaterially, deflects the string. It was found that the presence or absence of the signal magnet, when the amount of the primary current was kept constant, did not affect perceptibly the form of the shock or its value as a stimulus.

Mutostat. Inasmuch as in most of the experiments the shocks were delivered repeatedly, it was possible, by properly adjusting the speed of rotation of the lens wheel of the mutostat attachment to the galvanometer, to determine, without making a photographic record, the form and amplitude of the deflection of the string. The form of curve thus made obvious, could, when desired, be traced quite accurately, and, by placing a glass scale in front of the slit through which the light passes into the mutostat, the values of the ordinates of the curves, thus viewed, could easily be read off. These values, it was determined, owing to the further divergence of the rays in passing from the registering apparatus to the mutostat, were approximately 20 per cent larger than those registered on the sensitized paper. It was thus possible, by means of the mutostat, to carry on qualitative, indeed almost quantitative, preliminary experiments, and yet, whenever it was deemed advisable and at the proper moment, photographic records could be made for closer study or for reproduction. It is scarcely possible to overestimate the service which this attachment has rendered us in the elucidation of our problem.

Photographic registration. By means of photographic registration simultaneous records were made on bromide paper of the deflections of the string, of the contractions of the muscle, of such signals as were from time to time employed, and of the time usually in hundredths, sometimes in fifths or five-hundredths of a second. The rate of movement of the sensitized paper was in many of the experiments as high as 1 to 1.5 meters per second. The records obtained at this high speed were perfectly clear, and, when the curves presented clear criteria for measurement, it was possible to read them accurately to within 0.3 σ to 0.5 σ, but where the changes in direction were gradual, as for example, at the termination of a slow shock, the error of the measurement probably often became as large as 10.0 σ.

Proportionality of deflections to the fraction of current shunted into the galvanometer. It has frequently been necessary, in order to obtain shock deflections of amplitudes suitable for comparison in the galvanometer, to vary, during the course of an experiment, the position of the slide, C (see fig. 4), of the galvanometer shunt.

Data so obtained could not be of any value without proof that these brief deflections of the string are proportional to the amount of current so shunted into the galvanometer. That, at least under certain circumstances an almost exact proportionality does exist in the case of any given shock, may be indicated by means of a typical experiment.

Table II shows the effect of doubling the amount of current shunted into the galvanometer in the case (*a*) of the make shock of coil 1, a relatively slow shock; (*b*) of the break shock of the same coil; (*c*) of the make of coil 2, which arrives at its crest in approximately the same time as the break of coil 1; and (*d*) of

TABLE II

Showing the proportionality of deflections to the fraction of current shunted into the string galvanometer

COIL	COIL SEPARATION	FRACTION USED DENOM. = 51000*	DEFLECTION					
			Amplitude		Time to maximum		Duration†	
			B	M	B	M	B	M
	cm.		*mm.*	*mm.*	*σ*	*σ*	*σ*	*σ*
1	15.9	250	7.5	3.0−	3-4	6+ −7	20	50
1	15.9	500	15.0	5.5+	3-4	7.0	20	50+
2	8.3	250	7.5	2.5	2	3.5	13	45
2	8.3	500	14.5+	5 0	2	3.5	14	45

* The figures given under this heading are the numerators of fractions, the denominator of which will hereinafter be designated as in this table. They indicate the relative potential of the current shunted into the galvanometer.

† Approximate.

the break shock of coil 2, the quickest of all the shocks we have investigated. It will be noted that doubling the fraction of the current supplied to the galvanometer, in all cases practically doubles the amplitude of the deflection, the uncorrected time to maximum, and the total duration remaining practically unchanged.

Similarly, when the shunt into the string is so manipulated that the string deflections in two successive observations are to each other as 2 is to 1, it is found, upon reading the shunt, that the fraction of current sent into the string, as well as the corresponding deflections of the d'Arsonval galvanometer, in series,

are also to each other practically as 2 is to 1. It is possible that with very large differences the proportionality is no longer exact.

Interpretation of galvanometric records. Einthoven (5) states that the shortest oscillation period he has found it possible to obtain with the string galvanometer of normal size is 0.8 σ; the quickest completely damped deflection he pictures (6) requires 8.0 σ for its completion. Fahr (7), describing his ideal galvanometer in a recent paper on the theory of the string galvanometer, gives 6.0 σ as the time for the practical completion of a deflection that is just aperiodic, and adds that in the case of such a galvanometer a sensitiveness of 2.10^{-8} ampere for 1 mm. of deflection can be looked upon as very satisfactory. As we have employed the galvanometer, the completely damped string has usually attained its *full* deflection in from 6.0 to 8.0 σ, approximately, though the deflection was practically complete in about 5.0 to 7.0 σ, and the usual sensitiveness of 5 to 6.10^{-8} ampere compares very favorably with Fahr's ideal.[10] Since most of the shocks we have investigated attained their crests considerably faster than any of the deflections mentioned above, it is obvious that the galvanometer did not reproduce the shocks in their true form. In order to determine the true form of potential changes of brief duration, such as we are here concerned with, the recorded deflections must, therefore, be subjected to certain corrections. These corrections, it is commonly stated (8) can be made mathematically. So far as we have been able to determine, however, no one has published the method of correcting curves of the type produced by induction shocks. The methods used by Einthoven (9), as illustrated by his correction of the deflections caused by an instantaneous rise of potential, are not available here, since he recommends that the measurements of the angles of the curve begin 1.0 σ after the closure of the current; most of the shocks we have studied have already proceeded

[10] Our research was completed when Fahr's paper appeared. It may be stated here that our results confirm Fahr by demonstrating experimentally the limitations of the string galvanometer in the study of currents of very brief duration. The currents we have dealt with differ, however, in form from those treated mathematically by Fahr.

beyond their crests by that time. In the absence, therefore, of any exact guide, it has become necessary for us to develop for ourselves, very largely from personal experience, rough methods for the interpretation of our records. The principles that have guided us in this follow.

In our first attempts to derive the actual form of a shock from the form of its galvanometric record, it was assumed that the descending limb of the former (fig. 5, light line) intercepts the recorded curve (heavy line) approximately at its crest. Stated in another way, we assumed that the string deflection lags behind the actual potential changes; that it increases, though at a rate that varies from moment to moment, with the difference between the true and the recorded potentials, as long as the true is above the recorded potential; that it decreases from the moment the difference becomes negative. This would be true if, as in the case of the capillary electrometer, the string was without inertia. It would also be essentially true if the potential changes were not faster than the limitations of the string as determined by its inertia.

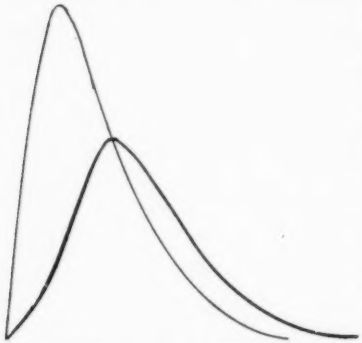


Fig. 5. Diagram showing the relation of a deflection (heavy line) to the current causing it (light line) when inertia is eliminated.

Results inconsistent with this assumption soon began to accumulate and eventually led us to question its validity. It was impossible, for instance, to reconcile with this view the observation that the process in the secondary coil may be practically or even entirely over at a time when the deflection caused by it is at its crest, and that a current of a known very brief total duration (say 0.4 σ) may produce a deflection that increases as long as 2.0 σ. Such results as these are undoubtedly attributable to inertia; yet as we have used the galvanometer, with a relatively good shunt around the string, the deflections due to

an instantaneous rise of potential as a rule have been entirely, or practically entirely, without fling. Obviously a galvanometer that exhibits no fling under these circumstances may, nevertheless, continue to move for some time after the impelling potential has ceased to act, when this occurs before the string has attained the position to which the uninterrupted action of the current would have carried it.

A more concrete idea as to the deficiencies of the string and as to the difficulties in the way of estimating these deficiencies may be obtained by examining the results of an experiment in which the deflection produced by the sudden but continued application of a constant current was compared with that of

TABLE III

An experiment illustrating some of the deficiencies of the string galvanometer in recording currents of brief duration

OBSERVATION	STRING DEFLECTION	
	Time to maximum	Amplitude
	σ	*mm.*
1. Instantaneous rise to constant potential	8.0	16.0
2. Same as (1), but circuit remains closed only 1.0σ	1.77	5.0
3. Amplitude of deflection attained by (1) after lapse of 1.0σ		3.0
4. Amplitude of deflection attained by (1) after lapse of 0.5σ		1.0
5. Same as (2) with higher potential	1.70	9.0

a momentary ($1.0\ \sigma$) application of the same current. Table III shows that in the latter instance, although the current was flowing for but $1.0\ \sigma$, the string continued to rise during almost twice that period ($1.77\ \sigma$), and that it rose to an amplitude that exceeded by 66 per cent the amplitude attained by the string $1.0\ \sigma$ after the closing of the current in observation 1. It is interesting to note that when the potential was increased until the amplitude of the deflection became 9 mm., and the current was again permitted to act upon the galvanometer during $1.0\ \sigma$, observation 5, the recorded time to maximum still remained as in observation 2.

Some of the factors modifying the deflection caused by currents of brief duration may be illustrated diagrammatically (fig. 6).

The diagram is based upon our own experience, and the values employed are taken from actual determinations. In the diagram, *OI* represents an instantaneous rise of potential to a constant value, *I;* it causes the string deflection, *OI'*, which, we will assume, attains its highest level in 8.0 σ. *OSB*, or *B'*, represents the potential changes of an induction shock (break of coil 3) that attains, we will assume, the same potential in 0.2 σ, and runs its course (at *B* or *B'*) in from 2.4 to 4.0 σ. *OS'C* is the

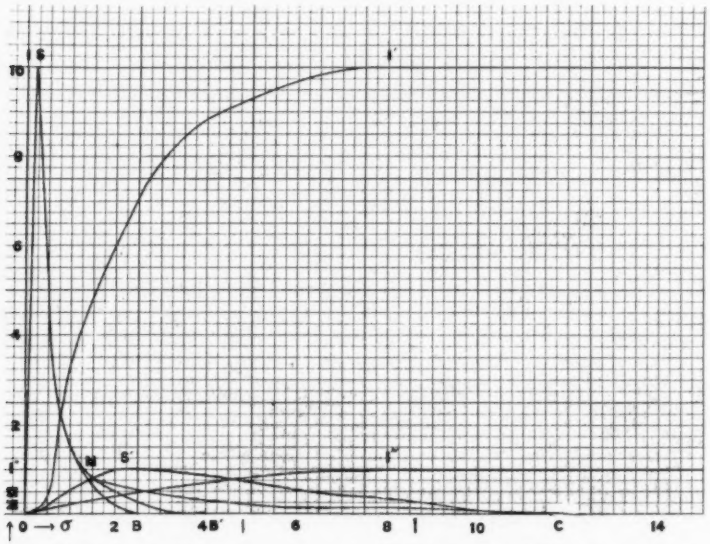


Fig. 6. Diagram illustrating some of the deficiencies of the string galvanometer. Description in text.

string deflection determined by this shock; it attains its crest in 2.2 σ and is completed in from 12.0 to 15.0 σ. If instead of an induction shock, we had passed through the galvanometer a constant current attaining its maximum potential instantaneously and lasting 0.2 σ the resulting deflection, it will be seen by comparison with *OI'*, would have been scarcely perceptible, at least, if the lag of the string were the only factor to be taken into consideration. A potential, *OI''*, rising instantaneously to

the same height as the deflection, $OS'C$, would have been recorded by the galvanometer in the form shown in the curve, OI'''.

The deflection $OS'C$ caused by the shock, OSB, is the resultant of several factors. Two of these factors are air and electromagnetic damping. If, however, these had been the only factors, the curve, OMC, that would have resulted, would have had its crest at the point, M, where the falling potential, SB or B', intersects the rising string, and its descending limb, MC, would have had a duration made up of (a) the time required by the string, in the absence of any actuating potential, to fall to the base line, namely 8.0 σ, plus (b) a certain factor determined by the residue, MB or B', of the shock, OSB, that still has its course to run.

Since, as a matter of fact, the string deflection has not attained its maximum at M, but continues to move for some time in its initial direction, it follows that other factors must be active in determining the time to maximum. One of these is fling. As has been indicated, we at first believed the galvanometer to be aperiodic, and for the reason that under ordinary circumstances a deflection caused by an instantaneous rise of potential usually showed no evidence of fling whatever; the limit of the deflection was approached asymptotically. That the galvanometer is not without inertia we discovered in the following way: During the course of a slow shock (make of coil 1 or 3), one that lasts fully 23.0 σ, the galvanometer circuit was opened to the current for a very brief period, let us say for 0.4 σ. The deflection thus obtained continued to rise not 0.4 σ but for a very much longer period of time, namely 2.0 σ and in 0.4 σ only one-half, approximately, of the final amplitude of the deflection had been attained. It is interesting to note that although this extra duration undoubtedly is dependent upon a number of factors, under the conditions obtaining in our experiments the time to maximum of such a deflection has usually been in the neighborhood of 2.0 σ. The string, in other words, continues to move in the initial direction for 1.6 σ after the current has ceased to act.

Returning now to the diagram, we note that the recorded shock, $OS'C$, in this case actually outlasts the period of rising

potential of *OSB* (0.2 σ) by slightly more than 1.6 σ. As a matter of fact the upward motion of the string lasts about 2.2 σ.[11]

In the case of brief currents, such as constitute induction shocks, it is therefore obvious that the galvanometer record will be too low, but, owing to fling, will reach its crest too late, and, owing to lag, will be too long. The necessary corrections will depend mainly upon the tension of the string and the form of the shock, and at best can be made only approximately.

In the foregoing discussion we have used for purposes of illustration one of the quickest of the shocks we have encountered. It is, however, obvious that all that has been said with regard to the quick shock applies qualitatively, though not quantitatively to the slower shocks.

PART II. SINGLE INDUCTION SHOCKS

Configuration and duration of induction shocks

Literature. Within the limits of this paper it will be possible to consider now, and but very briefly, only the one phase of the subject with which we are directly concerned, namely the time relations of induction shocks.[12] Some of the data with regard to the duration of shocks which we have succeeded in finding in the literature are given in Table IV, in which it may be seen that the duration and time to maximum of induction shocks, as determined by different investigators, vary within very wide limits. It would be a gratuitous task to attempt an analysis of the methods and of the coils these investigators have employed, with the object of determining the factors that have led them to such widely differing values. Suffice it to say that variable factors of sufficient magnitude to account for the great divergence can be found: of them we need mention only self-induction, magnetic hysteresis and secondary resistance. Physiologists and

[11] The discrepancy in this case is greater than in the foregoing experiment because in the former the current continued to flow until the shock was completed, whereas in the latter the current ceased after the completion of the 0.4 σ period.

[12] For full résumés of the theory of the induction coil the reader may be referred to the monographs of Armagnat (15), Fleming (16) and Jones (14).

clinicians usually quote the values determined by Helmholtz[13] by Bernstein,[14] or by Blaserna,[15] and fail entirely to refer to the slower figures of other investigators. This is somewhat surprising, since a careful study of the latter fails to reveal any obvious reason for entirely discarding them. For instance, it seems to us that the figures given by Beetz, and possibly also those we have obtained from Jones, have been controlled with sufficient care to entitle them to some consideration.[16]

However this may be, it is obvious that if any of the coils in use in physiological laboratories yield relatively slow shocks, a knowledge of this fact is essential to the interpretation of results

TABLE IV

Duration of induction shocks

INVESTIGATOR	BREAK		MAKE	
	Time to maximum	Duration	Time to maximum	Duration
	σ	σ	σ	σ
Helmholtz (10)	0+	0.100		
Beetz (11)	1.0			
Blaserna (12)		0.275		4.085
Bernstein (13)	0.2	2.0-3.0		
	0+	4.600	0.1	3.300
Jones (14)		2.500		
		3.700		10.000

obtained with such coils, especially when rapid or modified stimulation is employed.

At this place it might be well to call attention to some of the interpretations of the work of Helmholtz found in the literature, which to us seem to be not entirely justifiable. Before we had the opportunity of consulting the original papers of Helmholtz we had gained the impression through our reading that, accord-

[13] e.g., Martin (17).

[14] e.g., Garten (18).

[15] e.g., Englemann (19).

[16] Helmholtz states that his values are much smaller than some determined by Mariani and by du Bois-Reymond and that in his opinion these investigators did not properly insulate their coils; Beetz, on the other hand, believes that the slower values are not the result of error in observation or coil construction.

ing to Helmholtz, the time to maximum of the break shock is determined only by the duration of the sparking across the contacts caused by the extra current.[17] As a matter of fact Helmholtz merely states (p. 459) that according to theory the potential rise should be instantaneous. "Actually, however," says Helmholtz, "the rise is not instantaneous, but it is nevertheless much more rapid than the fall." At the same time he says that "the time to maximum is dependent mainly ("*wesentlich*")—he does not say, exclusively—"upon the time during which the vaporized metals are passing between the separating contacts."

THE GAP METHOD

Principles of the gap method. Although the string galvanometer is the quickest galvanometer we possess, it none the less fails to give an adequate idea of the real form of such rapid potential changes as occur during the course of an induction shock. And the methods for the correction of galvanometer records that we now possess are scarcely, we believe, sufficiently accurate to be of any considerable help in deducing the configuration of shocks from their records.[18] When using the string galvanometer for such purposes it is necessary, therefore, in order to obtain absolute values of amplitude and of duration, to resort to the same devices as have been used in the past with the slower, including the ballistic, galvanometers; recourse must be had to the principle of the differential rheotome. Then, however, the string galvanometer possesses some advantages over the slower instruments; in the case of currents of short duration its relative lack of sensitiveness is more than compensated by its relatively low inertia; whilst the quickness of its response makes possible, under

[17] See, for example, Martin (20).

[18] It might be added that this criticism applies with equal force to at least some of the potential changes occurring in connection with physiological processes. The time of development of the action current of nerve, for instance, as determined by approximate corrections of galvanometer records, lasts only 0.5-0.8 σ (21, 22). Deductions based upon the uncorrected time to maximum of deflections of the string galvanometer caused by such rapid action currents (see for example, Beritoff (23), can therefore have but little value.

certain circumstances, the obtaining of successive readings at rates as rapid as 100 per second.

In order to determine the form and amplitude of shocks, we have measured the amplitude of deflections caused by opening the galvanometer circuit for very brief intervals in different stages of the shock. This method will hereinafter be designated the Gap Method.

It is obvious that if the gap method is to yield unambiguous results, the duration of the gap must be short in relation to the duration of the phases of the shocks. In that way only would it be possible to eliminate the effects of the rising and falling potentials of the shock upon the deflection of the string. For when the gaps are sufficiently short the configuration of the potential changes to which the galvanometer is exposed, will be, to all intents and purposes, rectangular, and if such gaps all are of the same duration the amplitude of the deflections will be proportional to the amplitude of the rectangle of the shock that obtains during the gap.

On account of practical difficulties, this ideal condition cannot, however, be easily realized. The time to maximum of some shocks is probably as short as 0.15 σ. It would seem, therefore, that the gap ought to be considerably shorter in duration than 0.15 σ. But when it is shortened somewhat more than 0.15 σ the amplitude of the gap under circumstances which need not be discussed here, may be reduced down to the level of illegibility. It has been found, however, that for the determination of the time to maximum of a shock, it suffices to reduce the gap duration to from 0.1 to 0.2 σ. For when, in the case of a quick shock (break of coil 2 or 3), the gap interval is gradually decreased in successive determinations, the indicated time to maximum decreases until the gap interval becomes about 0.2 σ. With further reductions of the gap interval the indicated time to maximum remains practically constant. Despite this observation, we are of the opinion, in view of the foregoing theoretical considerations, that the time to maximum of the quickest of the shocks, as determined by the gap method is somewhat too long. In so far as

the slower shocks are concerned, it has been found that nothing is gained by reducing the gap interval to less than 0.4 σ.

Even the 0.1 σ gap interval cannot, however, indicate in correct relative proportions the *amplitudes* of the quicker shocks. This is due to the fact that the rate of fall (and rise) of potential is not the same in the different shocks, and that the maximum potential is maintained for an immeasurably short period of time. A diagram (fig. 7) will serve to make the difficulties clear. *OIC*, *OID* and *OIE* are three shocks all attaining their crests in the same time (0.16 σ) but declining at different rates. The illustrative gap, *AB*, lasting 0.1 σ, just includes the highest section of the shocks. It is clear that the amount of current in this gap varies with the slowness of the decay of the shocks. Consequently the slowest of the three shocks will cause the highest deflection. Inasmuch as the gap taken from the slowest of the shocks is practically rectangular in form, it also follows that any further slowing of the potential decline will be without effect on the amplitude of the gap deflection. It may be concluded, therefore, that the gap method will indicate too high relatively the amplitude of the slower shocks. It is consequently necessary to bear in mind in connection with what follows that the values as to the amplitude of the very quick shocks as determined by the gap method are too low and that this error is in proportion to the quickness of these quick shocks.

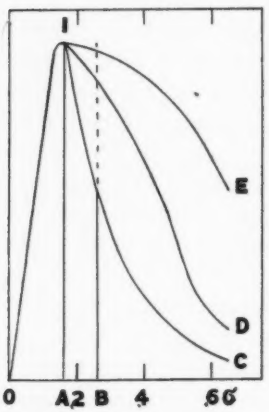


Fig. 7. Showing one of the effects of the configuration of a shock upon its amplitude as indicated by the gap method. Description in text.

Technique of the gap method. For the study of shocks by the gap method we have used a modification of the smooth rotary interrupter. Into a brass disc 500 mm. in circumference was inserted a non-conducting sector approximately 1 mm. wide. This was the narrowest sector of convenient size that could be

accurately made. The contact between the brush and the disc served to short-circuit the galvanometer. Therefore, the galvanometer circuit was open to currents only during 1/500 of each revolution of the disc. At the highest practicable speed, namely 20 revolutions per second, this amounted to 0.1 σ. The large (500 mm.) disc (the disc furnished with the rotary interrupter has a circumference of only 190 mm.) was employed in order to make it possible to use a gap lasting through short intervals and produced by a sector 1 mm. wide without running any risk of error due to overlapping of the make and break shocks. One and the same shaft drove this disc and its blank companion, also the make and break discs of the primary circuit and discs for short-circuiting the secondary circuit. In the main, amalgamated discs were employed. The brush on the gap disc could be moved concentrically with that disc by means of a screw, driven either by hand or, when advisable for the sake of uniformity, by a motor. Each 0.5 mm. advance of the brush was registered by means of a signal magnet, as was also the time in fifths of a second. Or the amplitude of the deflection at known positions of the brush was read in the mutostat. The rate of rotation is given in the records by the rate of the deflections of the galvanometer.

In order to determine the form of a shock a record may be made while the gap is steadily advancing from before the beginning of the shock to, or nearly to, the end of the shock. In this way in a single record a series of deflections is obtained, which increases to a maximum and then decreases (see fig. 8). By means of a simple calculation from data furnished by the record, the time relations of the shock are determined, and then, if desired, a reconstruction can be made showing the form of the shock, uniformly reduced as to amplitude, however (see fig. 9). The time intervals thus obtained are absolutely accurate to 0.1 σ, and by interpolation it is possible to make reasonably accurate readings down to 0.04 σ.

The duration of the shocks cannot be accurately determined by the gap method, partly because the amplitude of the deflections diminishes so very gradually that the end point is difficult

to find, and partly because a considerable potential is needed to produce a perceptible deflection in the brief period of time that the gap lasts. Nevertheless the results as to duration are of value in conveying some idea as to the relative duration of the shocks. Neither is a sharp reading of the time to maximum possible in the case of the slower shocks with rounded crests for in such instances the amplitude of the successive gaps in the vicinity of the crest changes very gradually. Despite these limi-

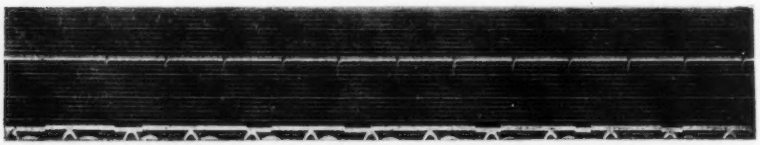


Fig. 8. Part of a record illustrating the gap method of determining the configuration of shocks. Analysis of the make shock of coil 2.

Uppermost line: Deflections produced by the opening of the short circuit of the galvanometer.

Lowermost line: Time in fifths of a second. The rate of rotation of the discs can be calculated from the number of string deflections occurring in a given time. Here it is such that 1 mm. of rotation occupies 0.388 σ. This is the duration of the gap.

Middle line: Record of the advancement of the gap brush. Each down stroke of the signal marks a 0.5 mm. advance of the brush over the face of the disc. The brush, therefore, gains on the disc at the rate of 0.194 σ per stroke of the signal.

The highest gap is attained in 3.5 strokes; the time to maximum is, therefore, somewhat less than 0.68 σ. The amplitude of the deflection of the full shock, from which these gaps were taken was 12 mm.

Records obtained at higher speeds of rotation do not, on account of their great length, lend themselves well to reproduction.

tations, however, the method yields results of considerable interest and value.

Results. The results obtained in this series of experiments may be best illustrated by quoting the essential parts of two typical sets of observations, one in which the gap interval was comparatively long (0.39 σ approximately), Table V, the other with a short gap interval (0.125 σ approximately), Table VI. It should be borne in mind in this connection that the form of a shock is profoundly influenced by certain conditions such as

TABLE V

Analysis of shocks by the gap method

1	2	3	4	5	6	7	8	9	10
COIL	SHOCK	ROTATION SPEED 1 MM. =	RECORDED AMPLITUDE OF FULL SHOCK	RECORDED AMPLITUDE OF MAXIMUM GAP	TIME TO MAXIMUM	DURATION BY GAP METHOD	TRUE RELATIVE AMPLITUDE	ABSOLUTE AMPLITUDE	RATIO Col. 5 / Col. 4
		σ	*mm.*	*mm.*	σ	σ	*mm.*	*volts*	
2	B	0.338	9.50	9.00	0.330 0.252	0.97+	99.9	0.87	0.950
3	B	0.392	11.00+*	8.60	0.392+	1.18+	95.5	0.83	0.780
2	M	0.388	12.00	3.10	0.680	4.10++	34.4	0.30	0.260
1	B	0.375	10.00	2.25	0.940 0.860	6.75+++	25.0	0.22	0.225
3	M	0.384	9.00	1.50	1.730	13.10++	16.6	0.14	0.167
1	M	0.388?	9-11	1.25	2.230 1.550 2.110 1.780	10.20++ 13.10++	13.9– 16.6	0.12– 0.14	0.140

* Passed out of field.

the strength of the shock, secondary resistance, etc. (see p. 446). In the two sets of observations used here these conditions were not entirely alike. This fact accounts in part for the differences in the results obtained in the two experiments. In part, however, they are probably attributable to the difference in the

TABLE VI

1		3	4	5	6	7	8	9	10
COIL	SHOCK	ROTATION SPEED 1 MM. =	RECORDED AMPLITUDE OF FULL SHOCK	RECORDED AMPLITUDE OF MAXIMUM GAP	TIME TO MAXIMUM	DURATION BY GAP METHOD	TRUE RELATIVE AMPLITUDE	ABSOLUTE AMPLITUDE	RATIO Col. 5 / Col. 4
		σ	*mm.*	*mm.*	σ	σ	*mm.*	*volts*	
2	B	0.1310	3.0	2.50–	0.164	†	40.0	0.50	0.83
3	B	0.1275	4.0	2.50	0.175		40.0	0.50	0.63
2	M	0.1240	11.5	1.30	0.310?		20.6	0.26	0.11
1	B	0.1290	12.0	1.60	0.348?		25.6	0.32	1.13
3	M	0.1230 0.1230	17.5?	1.25	0.700 0.860		20.0	0.25	0.07
1	M	0.1270	13.5	1.10	0.826		17.6	0.22	0.08

* Passed out of field.

† Records not continued long enough.

length of the gap, especially in the case of the shorter shocks such as the breaks of coils 2 and 3. Despite these differences the results of the two experiments here cited, as well as those of all the others, are quite satisfactory.

Time to maximum. Considering first the time to the first maximum gap, it will be noted that the sequence of the shocks, when arranged in the order of quickness, as in these tables, is the same in the two experiments. The break shock of coil 2 is the quickest, then follow the break of coil 3, the make of coil 2, the break of coil 3, and the makes of coils 1 and 3. This is also the order of the total duration of the shocks (Table V), which, it will be recalled, is determined only very roughly by this method.

The fact that the break shocks of the different coils attain their crests at different rates is of considerable interest in view of the current belief that in a well constructed coil the time to maximum of the break shock is determined by the duration of the sparking across the contacts, and therefore only by the nature of the contact.[19] In any one set of experiments as we have performed them, this condition has been kept constant; yet the time to maximum of the break shocks of coils 3 and 1 are longer than that of coil 2 by from 7 to 20 per cent and by from 112 to 244 per cent, respectively. The causes of these differences are not apparent; we can for the present only say that they are not due to any short-circuit in the primary that can be detected either by inspection or by a comparison of the calculated with the measured resistance. Be this as it may, the existence of differences in the time to maximum of the break shocks should render us cautious of any mathematical calibration of coils for physiological purposes, such as Martin's, that is based upon the assumption that the time to maximum of the break shock is constant; though it is possible that the error resulting from neglecting to take into consideration the inclina-

[19] It might be supposed that the strength of the extra current would also be a factor. That this is not the case is indicated by the fact that the spark at the break was much more intense with coil 3 than with coil 1. Yet the time to maximum of the break of coil 3 is much shorter than that of coil 1.

tion of the shock might not be so large as to affect to any considerable extent the end result of the calculation.

Contour of shocks. A few of the results have been carefully plotted for the purpose of determining the exact contour of the shocks. The results so obtained bring out some interesting facts, which may be summarized briefly as follows (see fig. 9, *a*, *b* and *c*): In the case of the very quick shocks, the breaks of coils 2 and 3 (exemplified by fig. 9, *a*), there is to be seen nothing resembling a plateau; the amplitude of the gap deflections, after the crest has been reached, begins at once to fall off. In the early parts the rate of this decline is almost if not quite as rapid as the rate of the ascent. This is in sharp contrast to what occurs in the case of the very slow shocks, the make shocks of coils 1 and 3 (exemplified by fig. 9, *c*). These present a very decided plateau, the maximum gap deflections showing relatively little change in amplitude through from 2.73 σ to 3.315 σ, while the decline from this plateau takes place very gradually. In general the length of the plateau varies as the duration and time to maximum of the shock.

Amplitude of shocks. The results obtained by the gap method with regard to the amplitude of shocks are most interesting. In each of the two experiments here cited the fraction of the current shunted into the string was kept constant; but in one (Table V) the attempt was made to obtain full shocks of approximately equal amplitudes by properly adjusting the distance between the primary and secondary coils, while in the other (Table VI), for reasons to be considered later, the shocks were of unequal amplitude. These shocks were then analyzed by the gap method. Owing to the errors inherent in the method there are some inconsistencies, but upon the whole the results are similar and are very striking. Analyzing here only one set of observations (Table V), it will be noted that although the amplitude of the deflections produced by the full shocks range between 9 and 12 mm., the gap deflections range between 1.5 mm. and 9 mm. The significance of these differences is best brought out by comparing the ratios of the deflection amplitude of the highest gap to the deflection amplitude of the full shock from which the gap is

Fig. 9. Showing the configuration of shocks as determined by the gap method and the effect of the secondary resistance on it. *a*, Break shock of coil 3. The gap period was 0.128σ. One division on the abscissa represents two gap periods, or 0.256. *b*, Break shock of coil 1. The gap period was 0.13σ. One division on the abscissa represents two gap periods, or 0.26σ. *c*, Make shock of coil 3. The gap period was 0.124. One division on the abscissa represents four gap periods, or 0.496σ.

The method of obtaining the data for these curves is described on p. 445. The secondary resistances employed were 129 ohms (●), 2129 ohms (×), and 5129 ohms (○). Each division of the ordinates in *a* and *b* represents a deflection amplitude of 1 mm.; in *c*, 2 mm.

The curves have not been corrected to show the real potential amplitudes of the shocks. An approximate idea of this may be obtained by multiplying the ordinates of *a*, *b* and *c* by 9.5, 2.5 and 1.6, respectively.

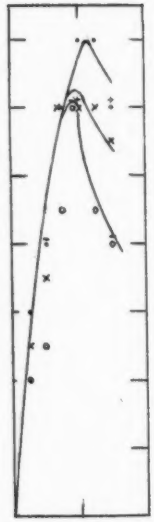


Fig. 9*a*

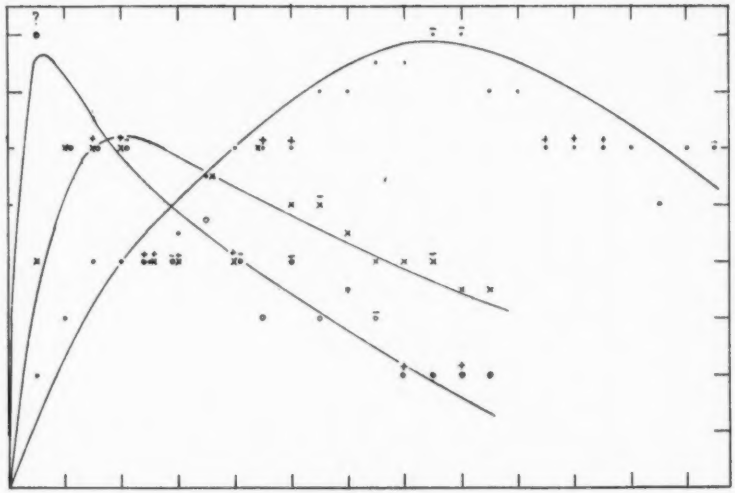


Fig. 9*b*

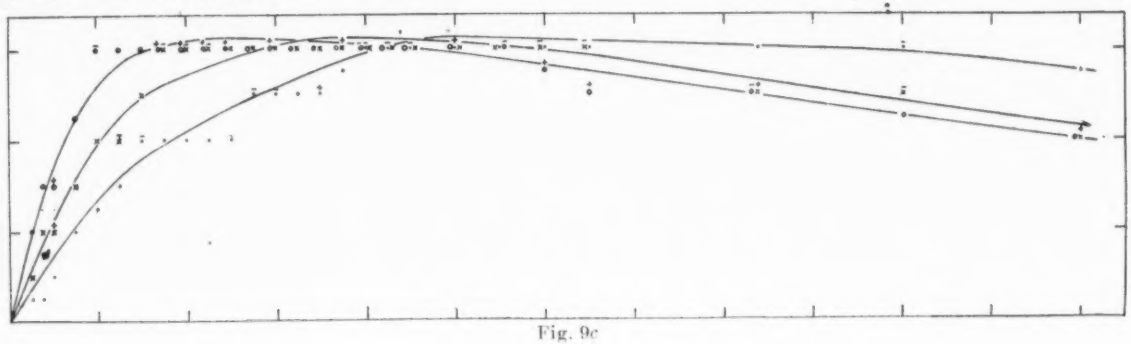


Fig. 9*c*

taken. This ratio (column 10) ranges between 0.95 and 0.14. If we assume for the present that the galvanometer reproduces accurately the slowest shocks, namely, the makes of coils 1 or 3, these ratios signify that the potential of the quickest of the shocks, the break of coil 2 must really have risen to more than 6.7 times the height of its record.

As a matter of fact, however, even the slowest shock is not reproduced by the galvanometer in its full amplitude. This is made clear by means of a procedure that may be termed the estimation of the true relative amplitude of shocks.

Estimation of the true relative amplitude of shocks. Under conditions similar to those that have obtained in a given experiment, the ratio is determined of the amplitude of the deflection caused by the uninterrupted action of a constant current to the amplitude of the gap deflection obtained from this current. By multiplying by this ratio the amplitude of the deflection produced by the same gap and obtained from a shock in the same experiment, the true relative amplitude of the shock is derived, disregarding the error resulting from the acuteness of the apex of the quicker shocks. To take a concrete example (Table V), a gap taken from a constant current that deflects the image of the string 108.6 mm. (derived by calculation from a smaller deflection) produces a deflection of 9.75 mm. The factor by which the gaps derived from the shocks are to be multiplied to obtain the true relative amplitude of the shocks is therefore (108.6 ÷ 9.75 =) 11.1. When this multiplication is made it is seen (column 8) that even the slower shocks (the makes of coils 3 and 1) are reproduced by the galvanometer somewhat reduced in height (9 mm. as compared with 13.9 to 16.6 mm.) The galvanometer, however, falls very far short of indicating the height of the quicker shocks; their recorded amplitudes (breaks of coils 2 and 3) attaining to only one-ninth to one-thirteenth of that of their true relative amplitudes.

Estimation of shock voltage. Having calibrated the galvanometer, and with the knowledge of the true relative amplitude of the deflection caused by a shock, it is possible to arrive at a rough approximation of the voltage developed by that shock.

Thus if, as was the case in the experiment tabulated in Table V, 1 millivolt gives a 3 mm. deflection, the maximum potential of, say, the particular break shock of coil 2 given in this table, is (column 9) 0.87 volt (true relative amplitude, 99.9, ÷ deflection produced by 1 millivolt, 3, ÷ the fraction of the shock shunted into the galvanometer, 1/26, ÷ 1000), whereas the maximum potential of the make shock of coil 3 that causes a deflection of the same amplitude as break of coil 2 above referred to, is only 0.14 volt.

Duration of shocks by short circuit of the galvanometer. The rheotome principle has been used in still another way for the purpose of determining the duration of shocks. By means of the smooth rotary interrupter, or the Helmholtz pendulum, a short circuit of the galvanometer is opened later and later in the course of the shock. The time elapsing between the change in the primary that induces the shock and the opening of the galvanometer to the shock at which the last perceptible deflection is obtained, gives the duration of the shock. In the case of the slower shocks it is impossible, owing to the very gradual return of the string to the zero level, to determine the end point by this method within 5.0 σ. Other conditions being the same, the higher the amplitude in which the shock is recorded, the greater will appear its duration as determined by this method. In order to minimize this error the string in some trials has been magnified 16,000 diameters by casting its shadow on a screen 4 meters removed from the galvanometer.

The results of one set of observations in which the pendulum was used to operate platinum contact keys for both the make and break shocks, are given in Table VII. The shocks are listed in the order of their duration. It will be noted that by this method also, the duration (column 5) of the different shocks varies in the same direction as their time to maximum, as given in the preceding section.

Configuration of shocks as indicated by uncorrected string galvanometer records. Although the string galvanometer does not reproduce induction shocks accurately, the uncorrected records of shocks made by means of this instrument are, nevertheless,

indicative of the relative form and duration of shocks from different sources.

Comparison of shocks by means of the string galvanometer can be greatly facilitated by recording them in approximately the same amplitude. This is readily accomplished by properly adjusting the fraction of the current shunted into the galvanometer, while viewing the deflection in the mutostat. Several series of shocks, controlled as to amplitude in this way, and with constant conditions in each series, though not in the different series, have been made. The results of two such series, one each made

TABLE VII

Duration (column 5) of shocks by the method of short-circuiting the galvanometer

1	2	3	4	5	6	7
COIL	COIL SEPARATION*	SHOCK	FRACTION USED	TIME BETWEEN OPENING OF KEYS	COLUMN 5 + 8.0 σ	DURATION BY RECORDS IN COMPARABLE EXPERIMENTS†
	cm.		*Denom.* = 51000	σ	σ	σ
2	8.2	B	950	1.670	9.670	11–13
3	13.6	B	950	2.424	10.424	12–16
2	8.2	M	950	7.878	15.878	15–18
1	14.5	B	950	13.030	21.030	20–23
1	14.5	M	950	29.690	37.680	32–38
3	13.6	M	950	32.120	40.120	30–40

* The coil separation is such as to give full break deflections all of approximately the same amplitude. The make deflections ranged between 7 and 9.5 mm.

† Taken from Table VIII b.

with platinum contact keys operated by the Helmholtz pendulum, and Martin's mercury key, are given in Table VIII.

Neglecting for the present the differences due to secondary resistance and to strength of shock, it is seen that in each series the shocks from the different coils show always the same relative differences amongst themselves, whilst the configuration of the shocks yielded by one and the same coil in the different series is always quite characteristic. Figure 10 shows clearly these differences in form and renders unnecessary any detailed description. In the table the shocks are arranged in the order of their quickness as measured on the records. When this table

TABLE VIII

Time to maximum and duration by recorded shocks

(a) Pendulum interrupter. Secondary resistance, 129 ohms

COIL	SHOCK	COIL SEPARATION	FRACTION USED	DEFLECTION		
				Amplitude	Time to maximum	Duration
		cm.	*Denom. = 2000*	*mm.*	σ	σ
2	B	13.25	116.700	6.50	3.0	13.5
		10.20	47.600	6.75	2.0	12.0
		7.00		6.50	2.0	13.0
2	M	13.25	685.000	7.00	5.0−	47.5
		10.20	270.000	7.00	5.0	55.0
		7.00	52.000	7.50	5.5−	51.5
1	B	15.30	14.700	8.00	5.0	26.0
		10.20	2.300	6.20	5.5	25.5
		7.00	0.095	7.00	5.5	31.0
1	M	15.30	76.500	7.00+	8.5	90.0?
		10.20	14.000	7.00+	8.5	90.0?
		7.00	6.000	7.25	9.0	82.0

(b) Martin's interrupter. Secondary resistance about 3000 ohms

			Denom. = 51000			
2	B	9.30	956.000	11.50	1.8–2.0	11.0–12.8
		0	20.000	11.30	2.0–2.2	13.0
3	B	20.00	953.000	11.30	2.0–2.2	12.0
		0	10.100	11.25	2.7–3.0	16.4
2	M	9.30	956.000	5.70	3.0	15.0
		0	20.000	5.85	3.0+	17.0–18.0
1	B	18.20	1532.000	11.50	3.2	20.0
		0	29.200	10.65	3.2–4.0	22.0–23.0
1	M	18.20	1532.000	7.00−	3.8–4.2	32.0–34.0
		0	29.200	7.00−	4.0–4.2	38.0
3	M	20.0?	953.000	3.80	4.0	30.0
		0	10.100	4.80	4.3–4.4	38.0–40.0

is compared with Tables V and VI, giving the time to maximum and the duration of shocks as determined by the gap method, and with Table VII, giving the duration of shocks as determined by the method of string foreshortening, it is seen that the sequence of the shocks is identical. The absolute values are, however, very different.

With regard to the duration of the shocks, when the results obtained by the latter method under one set of conditions (Table

VII) are compared with the results obtained by measurement of records of the full shocks under another, though similar, set of conditions (Table VIII) it is seen that, within the limits of error

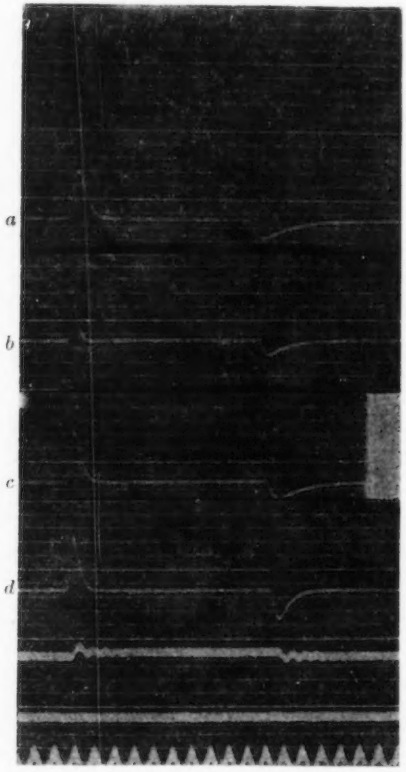


Fig. 10. Photographic records of the break and make shocks of (from above downward): (*a*) coil 1, (*b*) coil 2, (*c*) coil 3, (*d*) coil 3 without core. In order to economize space the time record (100 d. v. per second) is shown with only one of the curves. The rate at which the paper moved was, however, practically the same in all records. The break shocks are all of approximately the same height.

of the method, the difference in the case of each shock is practically a constant. As might have been predicted, this constant (see column 6, Table VII) is roughly the time required for the

string to complete its deflection under the influence of an instantaneous rise of potential, namely 8.0 σ. This observation is of significance practically in that it affords a means of determining roughly the duration of a shock from the galvanometric record of its deflection when the time required by the string to come to rest after an instantaneous change of potential is known.

The time to maximum on the record of the full shock probably cannot be employed to estimate the true time to maximum, for the reason that the former is determined not alone by the true time to maximum, but also by the contour of the portion of the shock following the crest. The fact that the order of the shocks in the two sets of observations is the same when they are arranged according to the time to maximum, is to be attributed to the fact that the duration of the shocks and their time to maximum always vary in the same direction.

Coreless coils. The effect of the removal of the core upon the configuration of the shocks has not been studied by the gap method. Records of the full shocks made with a view to comparing the shocks obtained from the coils under similar conditions, but with and without their cores, have, however, been obtained. In Table IX are collected the essentials of one such series. The Martin mercury key opened and closed the primary circuit. The amount of current shunted into the galvanometer in each case was such as would yield a break shock approximately 15 mm. high. The table shows that with but one exception, and in the case of this exception the difference is well within the limit of error of the method, the effect of the removal of the core is to shorten the shocks. Unfortunately, in this experiment, the record of the deflection of the string, when actuated by an instantaneous rise of potential, was made on paper that was moving too slowly to permit of sufficiently accurate measurement. It can, however, be stated positively that the deflection occupied not more than 7.0 σ. If we assume that the duration of the break shock of coil 2 with core in, has the same duration as the break shock in Table VII, namely 1.67 σ, the period of the string in the present case would become (8.14 − 1.67 =) 6.47 σ. A rough estimation of the effect upon the duration of shocks of

withdrawing the core is then given in column 9, Table IX. Although only approximate, this estimation is sufficiently exact to prove that the time relations of shocks from different coils without cores vary through almost as wide a range as when the cores are in place, and to justify the application of the considerations developed in the section of this paper dealing with repreated stimuli to shocks yielded by coreless coils.

Helmholtz side wire arrangement. Neither have we studied with any great care the shocks obtained from coils while equalizing the makes and breaks by means of the Helmholtz arrange-

TABLE IX

Comparison of shocks from coils before and after removing cores

1	2	3	4	5	6	7	8	9
CORE	COIL	COIL SEPARATION	SHOCK	FRACTION USED	DEFLECTION			COLUMN 8 − 6.47 σ
					Amplitude	Time to maximum	Duration	
		cm.		*Denom. = 51000*	*mm.*	σ	σ	σ
In	2	4.8	B	50	15.5	1.33	8.14	1.67
Out		6.5		1850	15.5	1.33	7.30	0.83
In		4.8	M	50	4.0	2.62	30.80	23.30
Out		6.5		1850	5.0	1.70+	21.50	15.00
In	3	11.0	B	80	15.5	1.49	7.72	1.25
Out		11.0		650	14.3	1.82	8.36	1.89
In		11.0	M	80	3.0	3.07	43.20	36.73
Out		11.0		650	5.0	2.73	33.60	27.13

ment. For the purposes of the present investigation it will suffice to call attention briefly to but one point: From the records of the shocks made with the string galvanometer, it would seem that in general these shocks have the same configuration as the make shocks yielded by the same coil. Their duration is, if anything, a bit longer than that of the unmodified make.

Relation of the contour of shocks to their value as stimuli

Literature. Induction shocks are electrical currents of brief duration in which the potential rises with relative rapidity to a maximum and then decreases somewhat more slowly. There

is every reason for believing (24) that an induction shock will behave both physically and physiologically in every way like a constant current of the same intensity and time relations, and that, therefore, the general laws of stimulation by electrical currents should be applicable in the interpretation of the results we have obtained when the shocks are used as stimuli. At the present time it cannot, however, be said that the laws of stimulation are as definite as they might be. It would seem that the du Bois-Reymond law attributing the stimulating action of currents entirely to the rate of change of intensity is giving ground to the views assigning to the quantity of electricity the first rôle in determining the stimulating action of electrical currents. It will be impossible to review this subject here;[20] we can consider only the most important facts that may play a part in the subsequent discussion of our own results.

1. In the first place it is stated that in the case of a constant current reaching its maximum potential instantaneously, the strength of current required for a minimal stimulation is very roughly inversely as the duration of the current (26–27).[21] According to Gildemeister (28) this applies only when the time of flow ranges within the brief period which he terms the *Nutzzeit*.[22] As to whether there is a limit to the reduction of the time of flow beyond which the tissues will not respond to a current of any strength whatever, is a question that seems still to be unsettled (29).

2. The rate with which the potential of the current rises is also a factor. To quote from Lucas (30): "As the current gradient is decreased the current strength required for excitation increases until a definite minimal gradient is reached. No gradient less steep than this will excite, even though the current-strength ultimately reached be as much as eight times as strong as the current-strength required to excite with an instantaneous increase in current."

[20] For a complete review of the subject the reader is referred to Cremer (25).

[21] Lucas (26) gives a review of the literature of this subject.

[22] Gildemeister defines the term *Nutzzeit* as the time through which a current must act in order to evoke a response.

3. It would seem that the rate of decline of the potential from the crest also manifests an effect upon the stimulating value of currents of brief duration; the effectiveness of a brief current, one ranging within the Nutzzeit, varying with the abruptness of the decay of the potential (29).

This view contradicts Helmholtz (31), who concluded "that the physiological effect of a break induced current is chiefly exerted by that part embraced within the ascending limb of the curve."

All three of the factors concerned with the determination of the stimulating value of brief currents undoubtedly play a part in the case of induction shocks. For this reason and because of its complicated configuration, it manifestly is impossible to infer the physiological effectiveness of an induction shock by mere contemplation of its form. It is very generally believed, however, that the steepness of the potential rise of an induction shock is of prime importance physiologically. This belief is founded largely upon the conclusion of Helmholtz as stated above, though in part also, upon certain inferences of which may be mentioned first, that based upon the relation obtaining between the form of the make and break induced currents and their apparent physiological efficiency; thus it is very generally held that of two equally effective shocks, the make must rise higher than the break, though so far as we know it has never been directly demonstrated by actual determinations of the potential amplitudes that such is the case. In the same category may be included the inference (32) which refers the differences in the efficiency of break shocks observed upon opening the primary circuit at different speeds, solely to resulting differences in the rate of rise of the potential of the shocks.

Gildemeister (33) has attempted to explain the well known modifying effect that the resistance in the secondary circuit has upon the stimulating value of shocks, by assuming, on the ground of theoretical considerations, certain effects of the resistance upon the contour of the shocks.

The same investigator has found by a comparison of induction coils of different sizes that the physiological stimulus may not

be the same even when the amount of the electricity delivered by the coils is identical, and in attempting an explanation of this result he states that "perhaps coils of different sizes yield curves of different form . . . . ."

So far as we have been able to determine no attempt has ever been made to correlate by means of direct experiments the configuration of a specific induction shock with its value as a stimulus.

General method. A basis for the determination of the relation between the configuration and the stimulating value of shocks may be obtained by assuming with v. Fleishl that minimal stimuli are equal physiologically. Proceeding from this assumption we have for each kind of shock found and then recorded simultaneously the threshold contraction of the muscle and the shock determining it. In another and later series of experiments the various threshold shocks were analyzed by the gap method. A single muscle was used throughout each experiment and the results were not considered satisfactory unless the irritability of this muscle, as determined by the threshold position of the coil, remained practically constant throughout the experiment. Naturally other conditions also were kept constant in each experiment.

An attempt to determine the relative physiological value of shocks by correcting string deflections. In the earlier experiments of this investigation we merely recorded the deflections produced by those full shocks which just rose above the threshold, and corrected the amplitude of the deflections of the galvanometer by means of a formula based upon the comparison of the tangents of the angle of inclination of the ascending limb of the deflection, it being assumed, at this early stage of the problem, that the break shock of coil 1 moved at the limit of accuracy of the string. We now know that the figures thus derived, undercorrected considerably the recorded deflections. Nevertheless, the results obtained are not without interest; they at least serve to indicate just how much can be derived in this connection from the records of induction shocks furnished by the string galvanometer as we then used it.

A typical experiment (see Table X, columns 1 to 7) may be cited to show the interrelation of the threshold shocks as regards their true times to maximum and their amplitudes, both recorded and as derived by the tangent formula. It may be seen in the table that the quicker shocks, when corrected (column 7), in general have the lower amplitudes. It was for this reason concluded in our preliminary report (34) that "the stimulating value of the shocks is dependent entirely upon their ascending limbs and obeys the du Bois-Reymond law."

It may be added here that when the make and break shocks are equalized physiologically by means of the Helmholtz side

TABLE X

Showing the amplitude of threshold shocks as corrected by the tangent formula and (approximately) by the gap method

1	2	3	4	5	6	7	8
COIL	SHOCK	THRESHOLD SEPARATION OF COILS	RECORDED TIME TO MAXIMUM	RECORDED DURATION	RECORDED AMPLITUDE	AMPLITUDE CORRECTED BY TANGENT FORMULA	REAL RELATIVE AMPLITUDE
		cm.	*σ*	*σ*	*mm.*	*mm.*	
2	B	12.5*	1.43	8.90?	2.2	7.2	20.9
2	M	7.6	3.45	39.45?	6.5	9.5	16.9?
1	B	12.7	4.64	22.64	9.5	10.0	21.3
1	M	8.7	8.00	60.00	15.0	15.0	21.3

* And rotated 35°.

wire, the amplitude of the deflection produced by shocks that are just threshold is the same as that of the unmodified make shock.

Relation between the configuration of shocks, as determined by the gap method, and their physiological efficiency. Subsequent experiments, in which the configuration of shocks of threshold stimulating value, was determined by the gap method, have demonstrated that the foregoing conclusion was unwarranted. Indeed, even before this was actually done, it was possible, by applying to the recorded shocks of threshold amplitude the corrections indicated in other experiments with the gap method, to get some insight into the relation between the true amplitude

and the physiological efficiency of shocks. Thus when the threshold amplitudes of the shocks listed in column 6 of Table X are multiplied by the factors indicated by an experiment in which the relative amplitudes of the whole series of shocks were determined (see Table V, column 10), it is seen roughly (column 8) by how much the tangent formula undercorrected the deflection and that the quicker shocks are quite as high as the slower shocks. The results obtained by multiplication of the amplitude of a deflection obtained in one experiment by a factor derived from another experiment, in view of possibilities of differences in conditions, cannot, however, be considered conclusive.

The experiment used for the compilation of Table VI is one of several in which threshold shocks were immediately analyzed by the gap method. The significant results of this typical experiment are as follows:

It is seen, in the first place, in accordance with the result referred to in the foregoing sections, that the *recorded* amplitude (column 4) of the full threshold shocks varies in the same direction as the time to maximum of the shocks as determined by the gap method (column 6).

On the other hand, the true relative amplitude of the threshold shocks, as determined by the gap method (column 8), and therefore the potential amplitude expressed in volts (column 9), are inversely as the time to maximum (and the duration) of the shocks, the threshold amplitude of the quickest shocks attaining, in this particular case, about twice the height (voltage) of the slower shocks. It should be added, however, that this is the largest difference we have observed. Usually the differences have been somewhat smaller, while in rare instances all of the threshold shocks have been of approximately the same height.

Relative amount of current in threshold shocks. For a satisfactory discussion of the foregoing results it is necessary to know something with regard to the quantity of current contained in threshold shocks.

(*a*) *By calculation.* If we regard shocks as triangles, an exceedingly rough approximation of the relative areas, and consequently of the quantity of current developed, can be derived from the

product of the duration of a shock by its threshold amplitude as determined by the gap method. The values thus derived will, however, be much too small relatively in the case of slower shocks for the reason that the crests of the slower shocks are well sustained, whereas the crests of the quicker shocks are immeasurably short. Table XI gives the results thus determined by combining data derived from two experiments. The table shows that despite the diminution in the absolute amplitude, the quantity of current in threshold shocks increases with the duration of the shocks.

(*b*) *By the ballistic galvanometer.* The same result is obtained, though much more strikingly, when, in one and the same experiment, a comparison is made of the deflections of a ballistic galvanometer (d'Arsonval) and of the string galvanometer, caused by threshold shocks of all kinds. A typical set of observations is here tabulated (Table XII). Attention is directed especially to the fact illustrated by the table that the two quick break shocks, those of coils 2 and 3, which have almost the same time to maximum and the same amplitude of string deflection, cause decidedly different deflections of the ballistic galvanometer. This agrees with the fact that the shock from coil 3 is longer in duration than that from coil 2.

TABLE XI

Showing the relative areas of threshold shocks as derived by calculation

COIL	SHOCK	DURATION	ABSOLUTE AMPLITUDE OF THRESHOLD SHOCKS	RELATIVE AREA ESTIMATED
		σ	*volts*	
2	B	1.670	0.5	0.835
3	B	2.424	0.5*	1.212
2	M	7.878	0.32	2.521
1	B	13.030	0.26	3.388
1	M	29.690	0.22	6.532
3	M	32.120	0.25	8.030

* It so happens in this experiment that the figures obtained for the voltage of the breaks of coils 2 and 3 are the same. Usually the voltage of the threshold break shock of coil 2 has been higher than that of coil 3.

TABLE XII

Showing the deflections of a ballistic galvanometer by threshold shocks

COIL	SHOCK	THRESHOLD DEFLECTION OF	
		String galvanometer	d'Arsonval galvanometer
		mm.	*mm.*
2	B	6	2
3	B	8	6
2	M	15–16	15.5–20
1	B	15	16
3	M	20	37
1	M	19	37

Discussion of the physiological value of induction shocks. To recapitulate the results recorded in the two foregoing sections, we note that shocks of the same physiological value may differ as regards:

1. Amplitude: the shocks with the shortest time to maximum and shortest duration and consequently those with steepest gradients, being the highest.

2. Quantity of current: the briefest and consequently the steepest shocks, despite their greater amplitude, containing the least current.

It follows that the *quantity of current*, while certainly playing a part, is by no means the only factor determining the physiological value of currents of short duration. In this the *rate of change of the potential*, possibly both the rise and the fall, play a very important rôle. It would seem, however, that the rate of fall of potential is relatively less important than the rate of rise. This is indicated by a comparison of the efficiency of the breaks of coils 2 and 3. The difference in the rate of rise here is relatively slight while the break of coil 3 decays very much more slowly than the break of coil 2. Yet their threshold amplitudes differ only very slightly, and despite the fact that threshold break of coil 3 may contain three times as much current as that of coil 2.

The relative importance of the quantity of current and of the rate of change of potential is seen in the typical series of threshold

shocks used for purposes of illustration, where the quantity of the contained current increases at least eighteen fold (Table XII), while the absolute amplitudes of the same shocks decrease at most only 2.3 times (Table XI, column 4). It is interesting to note that the real amplitude of a threshold make shock is always less than that of the threshold break shock of the same coil.

It has been stated that the so-called *Nutzzeit* plays an important rôle in determining the physiological value of currents of short duration. It may be inferred from the published figures (28) that the induction shocks herein employed have probably ranged within the special *Nutzzeit* of the gastrocnemius muscle. In the case of tissues, such as nerve, possessing a shorter *Nutzzeit*, the shocks might last longer than the *Nutzzeit*. In such an event it is possible that the stimulating value of induction shocks may obey rules differing materially from those herein deduced.

Effect of foreshortening[23] *shocks by short-circuiting the secondary circuit*

In the use of the induction coil one of the procedures commonly employed in the physiological laboratory in order to subject tissues to the action of the break shock only, is to short-circuit out the make shock. Inasmuch as we have reasons for believing that, as this procedure is commonly practiced, the make shock may outlast the period of the short-circuit, we have devoted some time to an investigation of the effect upon its form and stimulating value of foreshortening a shock.

The effect of foreshortening upon the configuration of shocks has been studied (*a*) by merely recording the string deflection caused by foreshortenings of known duration, and (*b*) by the gap method. The results obtained by the two methods supplement each other. The short circuits of the secondary coils were established and

[23] The term "to foreshorten" is employed to designate the shortening of a shock by eliminating a part of its beginning. This may be accomplished, for instance, by maintaining a short-circuit of the secondary coil while, and some time after, breaking or making the primary circuit, or by establishing the secondary circuit some time after the primary current has been made or broken.

broken by methods commonly used in the physiological laboratory, using for this purpose both the smooth rotary interrupter and platinum knockover keys operated by the Helmholtz pendulum.

(*a*) The results obtained by recording *the deflections caused by foreshortenings of known duration* in the case of shocks of medium strength, may be illustrated by two typical experiments, one made with a very quick shock, the break of coil 2, the other with a comparatively slow shock, the break of coil 1.

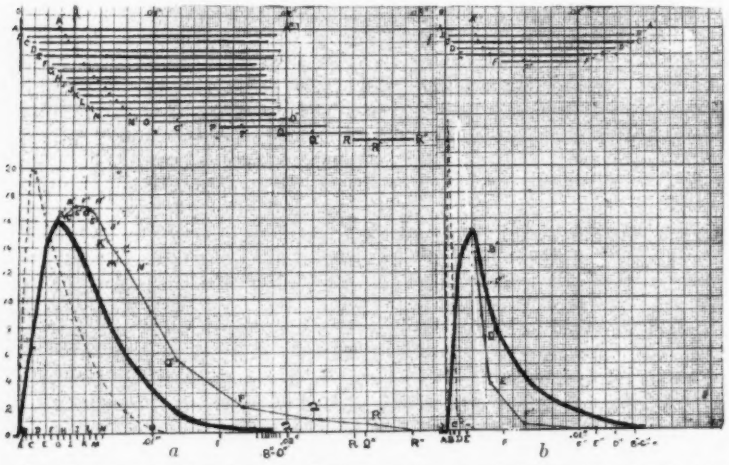


Fig. 11, *a* and *b*. Showing the effect upon the recorded form of a shock of different amounts of foreshortening in the case of the break shocks of coil 1 (*a*) and of coil 2 (*b*). Heavy line = recorded deflection of full shock. Light line = curve reconstructed from foreshortenings. Dotted line = assumed true potential changes. Further description in text.

Figure 11, *a* and *b*, shows the results obtained when these shocks, heavy lines, are foreshortened in successive trials by the time intervals indicated by the letters *B*, *C*, *D*, etc., on the abscissa. The crests and the terminations of the curves obtained with these foreshortenings are indicated by the dots, *B′*, *C′*, *D′*, etc., on the curves, and the dots, *B″*, *C″*, *D″*, etc., on the abscissa, respectively. For the sake of clearness the durations of

the deflections are also shown as straight lines placed directly above the corresponding curves, the three labeled points on each of the lines representing the beginning, the crest and the termination, respectively, of the successive trials.[24] By uniting the crests of the foreshortened shocks, curves are obtained (light lines) which, it will be noted, do not coincide with those of the unmodified shocks (heavy lines).

The reconstructed curve of the break shock of coil 1 (light lines) rises higher than the unmodified shock and lags considerably (2.0–3.0 σ) behind it. Furthermore it is interesting to note that the duration of the process of induction, which is set up by the break of the primary, remains unchanged, at least within the limit of error, which here is quite large, until the opening of the short circuit begins to occur late (10 σ) in the course of the shock (at O); and examination of the figure shows that in every case the part of the shock following the opening of the short circuit is shorter than the full shock. These facts may be taken to mean that the potential changes, both the rise and the fall, of a foreshortened shock are steeper relatively than those of the full shock, and that every foreshortened shock is higher than that part of the full shock from which it is taken.

We hesitate, on account of the number of assumptions involved, to draw any conclusion from the observation that the recorded time to maximum shortens progressively until the foreshortening amounts to 3.3 σ (at H) when the time to maximum is 0.7 σ less than the time to maximum of the unmodified deflection. It may merely be a coincidence that this shortening of the time to maximum agrees fairly closely with the true time to maximum of this full shock, as determined by the gap method, namely, 0.9 σ. May not this almost exact correspondence mean that the potential of a shock that is sufficiently foreshortened, rises to its maximum instantaneously?

Of greater significance in this connection is the observation that it is possible to obtain a considerable deflection when the

[24] It is difficult to determine accurately the termination of the shocks, and this difficulty increases as the deflections decrease in amplitude with the increasing foreshortening.

foreshortening (R) lasts longer than the string deflection that is determined by the unforeshortened shock, which in turn is considerably longer than the actual potential changes in the coil (dotted curve). This observation clearly indicates that a temporary short circuit of the secondary coil, when it is made to continue long enough, prolongs the process of induction.

At first sight it would seem that the results obtained with the break shock of coil 2, figure 11, b, differ very materially from those obtained with coil 1; for the reconstructed curve (light) is at every point lower than the deflection produced by the full shock (heavy), while the last foreshortened deflection obtainable, F, lies well within the termination of the deflection produced by the full shock. These differences are, however, attributable entirely, we believe, to the fact that in this case the true potential change is far quicker relatively than in the case of the break of coil 1. The fact that it is possible to obtain a deflection when the short circuit opens 4.3 σ (at F) after the break of the primary circuit, whereas the opening of a short-circuit of the galvanometer at the same time gave no deflection whatever, shows that the short-circuit of the coil has greatly prolonged the process of induction. This is also indicated when the duration of the last short-circuit (4.3 σ) is compared with the duration of this shock (1.67 σ) as determined by the string short-circuit method in comparable experiments (indicated roughly by dotted curve). It is however impossible to determine in this experiment, whether the true amplitude of the quicker shocks is increased by the foreshortening.

Approximation of the coils greatly prolongs beyond the figure mentioned above, the process of induction associated with a foreshortened shock. Some conception of the magnitude of such prolongation may be obtained from the results collected in Table XIII. In this particular set of observations the pendulum was used to open or close the primary circuit and then to open a short-circuiting key in the secondary circuit. The deflection of the string was either viewed in the mutostat or recorded photographically. Starting with the coils separated by a moderate distance, the keys were separated until the string deflection was barely perceptible. The coils were then approximated somewhat

and the keys again separated to the limit. This process was continued until the secondary coil was at zero. This method of procedure was employed in order to protect the string galvanometer from strong shocks.

Upon comparing the table in which these results are compiled (Table XIII) with Table VII, it will be seen that it is possible, by short-circuiting the secondary coil in the way above described, to increase the process of induction to more than ten times that occurring in connection with an unforeshortened shock of moderate strength.

TABLE XIII

Showing the maximum foreshortening at which deflections are still obtainable. The secondary coil was at zero.

COIL NUMBER	DURATION OF SHORT CIRCUIT AFTER WHICH DEFLECTION IS STILL OBTAINABLE	
	Break	Make
	σ	σ
1	110.0+*	130.0+
2	49.0	76.0+
3 with core	46.0	
3 without core	12.0	

* The plus (+) sign indicates that with the foreshortening specified the galvanometer still gave a large deflection, and that the foreshortened shock was still strong enough to cause a muscle to contract.

It will be shown below that increasing the strength of a shock by approximating the coils likewise increases the duration of a shock. It can, however, be demonstrated that the approximation of the coils in the present experiments is not the only cause of the lengthening of the process of induction. This is indicated by the results illustrated in figure 12, *a*, *b* and *c*. In this figure, *b* is the record of a break shock from coil 1, foreshortened 42.0 σ by short-circuiting a full shock whose deflection lasts 20 σ, as shown in *a*. It will be noted that despite the fact that the short circuit is broken long (22.0 + σ) after the completion of the unmodified shock, a considerable deflection (b) is nevertheless recorded. That the unmodified shock had completely run its course at this time is also substantiated by the results shown

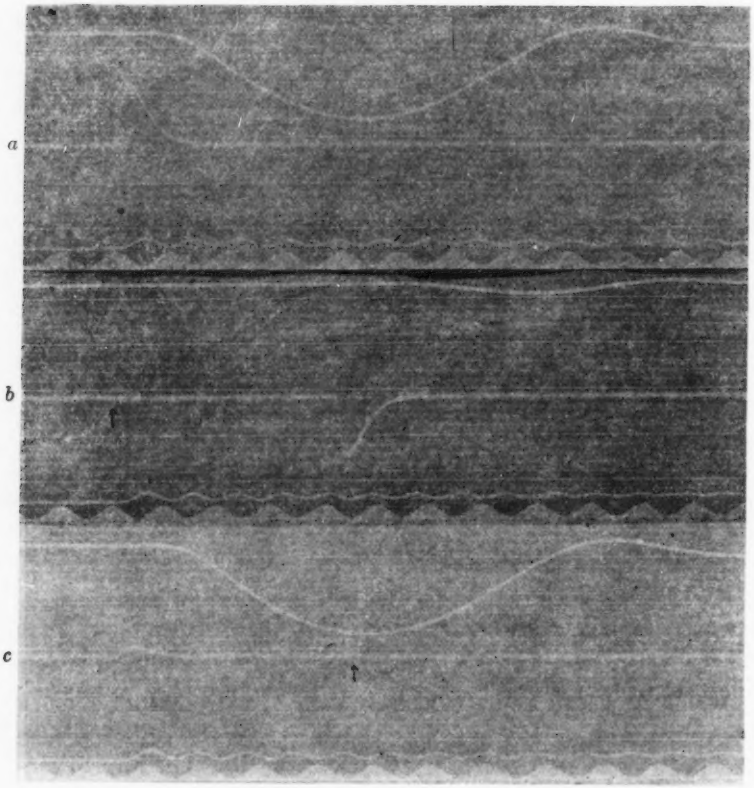


Fig. 12 *a*, *b* and *c*. Showing the prolongation of the process of induction by the foreshortening of strong shocks, as indicated by the string galvanometer and by the contraction of a muscle. In each part of the figure the tracings from above downward are: (1) Record of the muscle (the lever moves downward when the muscle shortens); (2) deflection of the string; (3) signal indicating roughly the break of the primary circuit; and (4) the time in hundredths of a second. The records are arranged over each other so that the opening of the primary circuit in all three is on the same vertical line. The string deflection in (*b*) is produced by a break shock, which inadvertently passes through the galvanometer in the wrong direction. For further description see text.

in c, which was obtained as follows: The same shock in this case was foreshortened, not by short-circuiting the secondary coil, but by short-circuiting the galvanometer and by the same time interval, namely 42.0 σ. At the same time a very much larger fraction of the total voltage was passed through the galvanometer. It will be noted that with the opening of this short circuit (at the point indicated by the arrow) the galvanometer was not deflected—the process in the coil had evidently ceased.

Analysis of foreshortened shocks by the gap method. It has been seen that the deflection caused by a shock that is foreshortened by short-circuiting the secondary circuit may be higher than that caused by the full shock. Since the duration of the shortened shock is decreased somewhat, this observation, as has been said, can mean only that the true potential of the shortened shock is higher than that of the full shock. The actual differences though, as determined by experiment, we have found to be considerably greater than we had anticipated. A few typical results obtained by the gap method will serve to make this clear (see Table XIV). In interpreting these data, the error resulting from the acuteness of the peak of the break in the case of the very brief shocks, should be recalled. Thus if, in the case of a quick shock, the record of a shortened shock rises to the same height as that of an unforeshortened shock, it may be concluded that the potential of the shortened shock rises higher than that of the corresponding full shock. Bearing this in mind, it can be concluded from the records and, in part, from the tabulated results: (1) That within the limit of error, the potential of the shortened shock rises instantaneously to its full height, which is at the same time practically the crest of the shortened shock[25] (see note †). (2) That at the instant the short circuit opens the amplitude of the shortened shock is higher, often very much higher, than the potential at the corresponding instant of the full shock (column 7). This holds true for both the break and the make shocks. (3) Attention should be called to the fact that the values obtained, as the table shows, depend to a certain

[25] We have not studied by the gap method the effects on the form of a shock of foreshortenings lasting less than the time to maximum of a shock.

extent upon the secondary resistance, the effect of the short-circuit upon the real amplitude of the shock increasing with the resistance in the secondary circuit. This is not surprising when it is realized that the short-circuit effect is in reality a manifestation of secondary resistance. (4) That the potential of the shortened shock falls away more rapidly than the potential in the corresponding region of the full shock (see note ||). It should be added that the decay of the potential of a foreshortened shock has not been studied systematically.

TABLE XIV

Showing some of the results obtained in an analysis of foreshortened shocks by the gap method

1	2	3	4	5	6	7	8
COIL	SHOCK	COIL SEPARATION	SECONDARY RESISTANCE	RECORDED AMPLITUDE OF SHOCK*	MAXIMUM GAP AMPLITUDE†	CRITICAL GAP AMPLITUDE	FORESHORTENING
		mm.	*ohms*	*mm.*	*mm.*	*mm.*	σ
1	B	11.5	2,129	20.0	2‡	‖	0.000
				22.0	10		2.300
1	B	11.5	129	24.0		10–12	0
				26.0		12–14	2.300
2	B	8.0	5,129	18.0	14	0	0
				18.0	12–	9	0.186
2	B	8.0	5,129	18.0	14	3	0
				18.0–	16	9	0.124
3	B	11.2	5,129	15.0	10		0
				15.0	11		0.124
3	M	12.0	2,129	5.5	7	5	0
				15.5	12	11	2.200
3	M	6.5	50,129	4.0+	0+		0
				15.5	10		2.200

* The deflections of the full and foreshortened shocks were magnified 500 diameters, while the gap deflections were magnified 1000 diameters.

† The deflections produced by the first 1 mm. gap of the foreshortened shock (the critical gap) has always been as high as any obtained, at least, within the limit of error of the method. The experimental error here is 25 per cent, since it is impossible to adjust the brush to the gap within 0.25 mm.

‡ The fraction of the current shunted into the galvanometer here was just four times that used in the second observation of this series.

|| With the gap brush set so that the gap opened 0.3σ later than the critical gap, the gap deflection of the full shock was still 2 mm., whereas that of the foreshortened shock had decreased from 10 mm. to 6 mm.

The results obtained in this part of our investigation are not entirely in accord with the views of Gildemeister, who states that according to theory the break induction shock falls away more slowly when the resistance, in the form of a shunt to the object, is made small, and that the make shock is influenced in just the opposite way. Our results show clearly that the introduction of a low resistance shunt prolongs the induction processes associated not alone with the break of the primary circuit, but also with the make. We have not determined the effect of intermediate shunt resistances upon the duration of the secondary processes.

Foreshortened shocks; physiology. Of the changes wrought in a shock foreshortened by temporarily short-circuiting the secondary circuit, three, namely, the increased steepness of the potential rise, the relatively rapid fall of the potential and the greater height of the crest would presumably have the effect of increasing its physiological efficiency over that of the full shock; whereas one only, namely, the shortening of the duration of the part of the shock acting on the tissue presumably would diminish its value as a stimulus. Obviously, it is impossible to predict from these facts the physiological consequences of foreshortening a shock.

Experiment shows that foreshortening, when properly placed, increases the effectiveness of all shocks excepting perhaps that of the very quickest of the breaks, those of coils 2 and 3.

The physiological effects of foreshortening a shock may be demonstrated in two ways: (1) The secondary coil may be placed in the position at which the full shock is a threshold stimulus, and then the result of the foreshortenings upon the height of the contractions may be determined. (2) The threshold position of the secondary coil may be found for a given full shock and for the different degrees of its foreshortening.

1. Effect of foreshortening upon the height of contraction. A very convenient and comprehensive way of demonstrating the effectiveness of a given shock when foreshortened, is to determine the variations in the height of contractions as the foreshortening is made to change progressively. A method of accomplishing

this, that is sufficiently accurate for our purposes, consists in using as the short-circuiting key the make-break or break-make interrupter revolving at a known speed, and in carrying the spring brush across it parallel to its axis at a uniform speed, by means of a screw drive. The progress of the brush across the face of the cylinder may be recorded electromagnetically. The amount of the foreshortening may then be calculated from the data furnished by the record to within 0.2 σ. This method, as we have used it, necessitated a rather rapid rate of stimulation of the muscle, and the fatigue that resulted possibly obscured some of the finer time relations. An accurate knowledge of

a *b*

Fig. 13, *a* and *b*. Showing the effect upon the height of contractions of a muscle of foreshortening the break shock of coil 1.

The record reads from left to right. The foreshortening changes regularly, the extent of its intrusion into the shock being indicated by the numbers, to wit:—at 0 the foreshortening ends (*a*) or begins (*b*):

1 = 2.8 σ foreshortening,
2 = 5.6 σ foreshortening,
3 = 8.4 σ foreshortening,
4 = 12.0 σ foreshortening,
5 = 14.0 σ foreshortening.

In part *a* the short-circuit is receding from a point in the shock (14.0 σ) at which the foreshortened shock is below the threshold. When the foreshortening is reduced to 12.0 + σ the shock first rises above the threshold. The stimulating value increases until the foreshortening has receded to 2.8 σ. The height of contractions then rapidly diminishes until, coincident with the disappearance of all foreshortening, (at 0), it has reached threshold amplitude. In part *b* the foreshortening is advancing into the shock.

these is not, however, required for the elucidation of the questions that concern us here. Indeed, the time relations are influenced by so many factors which never can be exactly controlled in physiological experiments, such, for example, as the form of the shock as determined by secondary resistance and strength,

the *Nutzzeit* of the preparation, etc., that little of value can come of their accurate determination. This method does, however, give a very good general idea of the significant time relations.

The record reproduced in figure 13, *a* and *b*, a full description of which is given in the legend, is typical of the experiments in

TABLE XV

Showing the physiological efficiency of the make shock of coil 2, and the spring deflection produced by it, while it is being gradually foreshortened. The secondary coil is in the position (6.1 cm.) at which the full shock elicits a threshold contraction

AMPLITUDE OF DEFLECTION	FORESHORTENING	HEIGHT OF CONTRACTION
mm.	*σ*	*mm.*
18.0	0	1+
18.0	0+	1+
18.0	0+	0.5
18.0	0.28	1+
18.0	0.56	19.0
17.5	0.84	23.0
17.0	1.12	30.0
16.5	1.40	32.0
16.0	1.68	33.0
15.0	1.92	33.0
15.0	2.24	34.0
14.0	2.52	34.0
13.0	2.80	34.0
12.5	3.20	28.0
12.0	3.60	27.0
10.5	4.00	24.0
9.5	4.40	21 0
9.0	4.80	14 0
8.0	5.20	3.0
7.5	5.60	2.0
7.0	6.00	1.0
6.0	6.40	0 0

which, by this method, the contractions of the muscle were recorded on smoked paper. In Table XV the results are presented of a typical experiment in which the contractions of the muscle and the deflections produced by the shock were recorded simultaneously on sensitized paper. The records are too long for reproduction.

These experiments illustrate the three important results of this series:

1. A shock that is just threshold may elicit a very high contraction when it is properly foreshortened by a temporary short-circuit of the secondary coil.

2. This increased physiological efficiency, due to foreshortening may last until the foreshortening of a threshold shock occupies a period of time that is almost as long as the unmodified full shock itself, though this is by no means always the case. Thus in the case of the experiment illustrated by figure 13, contractions are still obtained when the shock is foreshortened 12.0 σ, while the duration of the full shock was presumably only 13.0 σ. And in the case of the experiment illustrated by Table XV the last contraction was obtained when the shock was foreshortened 6.0 σ; the duration of this shock was approximately (recorded duration, 20.0 σ − 8.0 σ =) 12.0 σ.

3. The foreshortened shock of greatest efficiency is not the one in which the short circuit lasts only to the crest of the unforeshortened shock; indeed the efficiency increases for some time beyond this point. Thus in the case of figure 13 the maximum efficiency was reached when the foreshortening amounted to 2.8 σ, whereas the time to maximum of the unforeshortened shock was probably less than 2.0 σ; and in the case of the experiment analyzed in Table XV the maximum efficiency was reached when the foreshortening amounted to from 2.24 to 2.8 σ; the time to maximum in this case was certainly less than 1.0 σ.

It has been stated that we have rarely, if ever, succeeded in demonstrating any increase in the efficiency of the very quick break shocks as a result of foreshortening. These quick shocks can, however, be foreshortened somewhat (0.6 σ in the case of the break of coil 2) before a decrease in their stimulating value occurs. Since the true time to maximum of the break shock of coil 2 is not over 0.2 σ, it at least may be said of these quick shocks that an advancing foreshortening does not *decrease* the physiological efficiency of the shock until it has passed well beyond the crest of the shock.

2. Threshold position of the secondary coil with shocks foreshortened by shunting the secondary circuit. In these experiments the frog's gastrocnemius muscle was stimulated and the threshold position of the secondary coil was determined for the full shock, and then with progressively greater or lesser degrees of foreshortening. The results obtained confirm and supplement those described above. An illustrative experiment in which the amplitude of the deflection caused by the shock was also determined, is given in detail in Table XVI. The break shock of coil 1 is here investigated; similar results have, however, been obtained with all of the other shocks with the possible exception of the breaks of coils 2 and 3. The experiment in its first part was performed by setting the *secondary coil* in the position indicated and then varying the distance between the primary key and the

TABLE XVI

Effect of foreshortening on the threshold position of the secondary coil and on the threshold amplitude of deflections. Break of coil 1

FORESHOPTENING THAT PRODUCES A THRESHOLD CONTRACTION	SEPARATION OF COILS	AMPLITUDE OF DEFLECTION
σ	*cm.*	*mm.*
43.0	0	16.0
37.0	2.5	14.5
31.0	5.0	14.0
23.0	7.5	11.0
19.0	9.0	10.0
16.0	10.0	10.0
14.0	11.0	10.0
12.0	12.0	9–10
10.0	13.0	10.0
8.4	14.0	9.0
5.5	15.0	9.5
4.0	16.0	9.5
	17.0*	
3.0	16.0	12.0
1.8	15.9	11.0
0.6	14.8	15.0
0.0	13.9	16.5

* With this separation of the coils the stimulus falls below the threshold of the muscle.

short-circuiting key in the secondary circuit until a contraction of threshold amplitude was obtained. For the last four observations the *keys* were set in the positions indicated and the threshold position of the coil was then found. The last observation in the table gives the threshold values when the unforeshortened shock is the stimulus.

Reading the table, for the sake of convenience, from below upward, it will be observed that as the foreshortening is increased, the coils at first can be separated until the optimum foreshortening of 3.0 σ,[26] roughly, is reached, when the distance between the coils is 16 cm. as compared with 13.9, the threshold position for the full shock. With further increase in the foreshortening, however, the coils must be approximated in order to elicit a contraction.

It should be noted that a contraction is still obtainable when the keys are separated by a distance (43.0 σ) that greatly exceeds the duration of the full shock, as indicated by a record of the deflection obtained with the coil at zero position (20.0 σ − 8.0 σ (?) = 12.0 σ). And it is very unlikely that this figure represents the limit of effective foreshortening obtainable with this coil. Although we have not put this to the test of experiment, it seems more probable that further increase in the strength of the shock, obtained, for example, by increasing the amount of the primary current, would have permitted of even further foreshortening.

Similar observations with other coils and shocks indicate, as might have been expected, that the limit of effective foreshortening bears some relation to the duration of the unforeshortened shock (see Table XIII).

Comparative amplitude of threshold shocks, foreshortened and unforeshortened. With regard to the real potential amplitude of threshold foreshortened shocks, it should be stated that in such prolonged experiments as those just described must necessarily be, it is impossible to employ the gap method with any reasonable hope of success, for the reason that fatigue would inevitably result before a full set of observations could be made and would

[26] Compare with the corresponding figure (2.8 σ) obtained by the preceding method.

interfere with the interpretation of the results. In the absence of data obtained by the gap method, however, a conclusive analysis of the recorded amplitude of the deflection is almost impossible. Since, however, foreshortening a break shock of coil 1 at first increases markedly the amplitude of the potential and shortens the time to maximum, and since these changes are usually associated with a slight increase in the recorded amplitude (see fig. 11, *a*), the fact that in the present experiments (see Table XVI) the threshold deflection decreases with increasing foreshortening, may be taken to mean that the change in potential amplitude, until the foreshortening amounts, in this particular instance, to almost 4.0 σ, is comparatively slight. The increase in the recorded amplitude of deflections, seen in Table XVI, when the foreshortening becomes more than 8.4 σ, is an interesting phenomenon. It would, however, be futile to speculate as to its cause in the absence of any clear conception of the configuration of the associated potential changes.

Relative efficiency of shortened makes and full breaks. It has been seen that properly foreshortening a shock may increase its physiological efficiency. It is very interesting to note in this connection that we found it was possible in the case of one coil, at least, to obtain a foreshortened *make* shock of an efficiency that was equal to, or even greater than, that of its own break shock.

Table XVII gives a case in point. In this case the threshold position of the secondary coil (coil 1) for the optimum foreshortening of the make shock is 17.3 cm. as compared with 16.7 cm., the threshold position of the coil for the full break shock, and 12.5 cm. for the full make shock. Some idea as to the magnitude of the increase in the efficiency of a shock that may result when it is foreshortened, may be gained from the observation that the recorded amplitudes of two make shocks, one obtained with the coil at 12.5, the other with the coil at 17.3, the positions occupied by the coils in this experiment, are to each other as 5 is to 1; that is to say, the shortened shock, when judged by the amplitude of the deflection it causes, is five times as effective as the full shock. These facts, as will be made clear

TABLE XVII

Showing the relative physiological efficiency of full and foreshortened shocks. Coil 1

SHOCK	THRESHOLD SEPARATION OF COILS	STRING DEFLECTION	
		Amplitude	Time to maximum
	cm.	*mm.*	*σ*
Full M	12.5	15.0	7.0
Full B	16.7	10.5	3.0
M shortened 8.0 σ*	17.3	4.5	1.0-2.0
B shortened 5.0 σ*	18.8	5.5	1.0–

* Optimum foreshortening as determined by trial.

later, are of considerable practical importance in connection with the subject of repeated stimulation. In the case of coils 2 and 3 we have not succeeded in obtaining foreshortened make shocks that are quite equal in efficiency to the full break shock.

Because of its significance in relation to a subsequent section of this paper, brief reference may also be made here to the relative stimulating values of the make shock, of the make foreshortened for some time, and of a short section of the first part of such a foreshortened make. To illustrate these values, the results of a typical experiment, Table XVIII, will be quoted. It is seen in the table that the first 1.0 σ of a shock foreshortened 20.0 σ by short-circuiting the secondary coil, is quite as effective physiologically (as indicated by the threshold position of the coil) as the whole of the foreshortened shock, which in turn is very much more effective than the full shock itself. It should be added that the difference in the threshold positions of the

TABLE XVIII

Showing the increased effectiveness of a foreshortened make shock and of a fraction thereof. Coil 1

STIMULUS	COIL SEPARATION	CONTRACTION	STRING DEFLECTION
	cm.		*mm.*
Full shock	11.0	Threshold	24++
Shock shortened 20.0 σ	13.55	Threshold	7-8
First 1.0 σ of shock shortened 20.0 σ	14.0	Threshold	6
Full shock	14.0	0	9

coil for a shortened shock and for a similar short section of the shortened shock, is usually less than that obtaining in this case; it generally falls within the limit of the experimental error. It may be concluded, therefore, that the whole shortened shock and a small section of the shortened shock may be equally effective, whereas both may be much more effective than the full shock.[27]

Aftershortened shocks.[28] For the interpretation of experiments with repeated shocks it is essential also to have some idea with regard to the effect upon the physiological efficiency of a shock, especially of the make shock, of cutting it short before it has run its full course. We have, therefore, studied, *a*, the effect upon the amplitude of contractions of aftershortening a shock, which, when full, elicits a submaximal contraction and also, *b*, the effect of aftershortening a shock upon the threshold position of the secondary coil.[29]

It should be borne in mind in this connection that the aftershortening not alone diminishes the amount of current contained in the shock, but also changes its form by substituting for the gradual decline of potential a precipitous decline. According to Gildemeister the latter change, at least, when it is made to fall within the *Nutzzeit* period, should have the effect of increasing the potency of the shock. It may, however, be said once and for all that since a shock that is being gradually aftershortened, at no time has shown any greater stimulating power than the whole shock, it is justifiable to conclude that the sudden fall of potential, when it is made to occur as in these experiments, does not increase the effectiveness of the shock as a stimulus.

a. A typical record (fig. 14, *a* and *b*) and some of the data derived from the experiments in which the first method has been used (Table XIX) may be reproduced by way of illustration.

[27] It is obvious that the results obtained in an experiment of this kind are subject to such modifications as may be exerted through the *Nutzzeit* phenomenon.

[28] The term "aftershorten" is used to designate the cutting short of a shock either by short-circuiting or by breaking the secondary circuit some time after the make or break of the primary circuit that induces the current in the secondary circuit.

[29] The methods employed to accomplish this are similar to those described in the section dealing with foreshortened shocks.

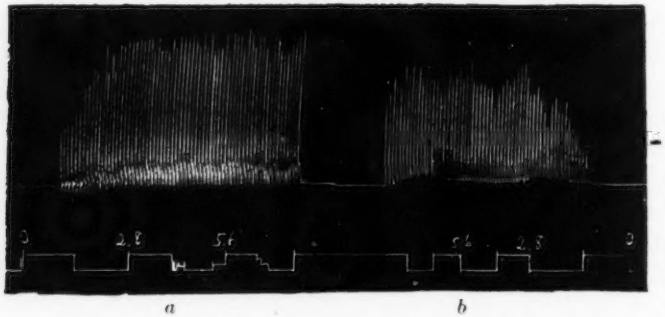
TABLE XIX

Showing the time of the earliest aftershortening that produces a maximal effect

COIL	COIL SEPARATION	SHOCK	TIME TO FIRST MAXIMAL CONTRACTION
	cm.		*σ*
2	11.0	B	0.2-0.4*
2	5.2	M	1.0-2.0
2	5.5	M	2.2*
1	12.0	B	1.5
1	12.5	B	2.2-2.5*
1	8.5	M	2.5-3.0

* From photographic records; all others from tracings on smoked paper.

It will be noted that the time through which a shock must act in order to produce its maximal effect is definitely dependent upon the contour of the shock; in every case it is much larger



a *b*

Fig. 14, *a* and *b*. Showing the change in the amplitude of contractions of a muscle stimulated with the make shock of coil 1 while it is being steadily aftershortened from the beginning toward the end of the shock in *a* and from the end to the beginning of the shock in *b*. The numbers given in connection with the signal indicate in thousandths of a second the degree of advancement of the aftershortening into the shock.

than the time to maximum and much shorter than the duration of the full shock. Evidently a shock continues to exert an effect upon tissues for an appreciable time beyond its crest. Inasmuch as the absolute duration of this critical period must bear some relation to the so-called *Nutzzeit*, it is probable that it will be found to vary with the tissue stimulated.

b. If the aftershortening be made to proceed through the shock in steps from the end toward the beginning of the shock, and if the threshold position of the coil be determined at each step, it is found (see Table XX) that for some time the threshold remains practically unchanged; a time is eventually reached, however, when the coils must be approximated in order to obtain a contraction. The duration of the aftershortening at this time agrees very closely with the duration of the aftershortening at the critical point, as determined by the preceding method. Thus

TABLE XX

Showing the threshold position of the secondary coil with different amounts of aftershortening. Make of coil 1

TIME OF BEGINNING OF AFTERSHORTENING	THRESHOLD POSITION OF COIL	AMPLITUDE OF DEFLECTION
σ	*cm.*	*mm.*
0	10.50*	
46.0	10.30	16.0+
28.0	10.25	16.5
15.0	10.20	17.0
8.0	10.20	17.0
6.0	10.15	16.5
4.0	10.30	12.0
2.0	9.70	6.0
1.0	3.60	3.5

* This observation was made some time before beginning the series.

in the experiment here cited the threshold, as indicated by the separation of the coils, changed when the aftershortening began between 2.0 and 4.0 σ after the beginning of the shock; the comparable figure by method 1 (see Table XIX) is 2.5 to 3.0 σ.

Effect of approximation of the coils on the configuration and relative stimulating value of shocks

An effect of strength of shocks upon their duration, as indicated by the records, is obvious in all of the experiments we have performed; increasing the strength of the shock has almost invariably lengthened the curve (see Table VIII). This effect of the

strength of shocks upon the form of the curve, if substantiated, might manifest itself upon the stimulating value of shocks; for presumably a stronger shock would contain more current, with a given amplitude, than a weaker shock. A few experiments, therefore, have been performed with a view to determining roughly the effect of the strength of shocks as determined by the distance of the secondary from the primary coil upon their relative physiological efficiency.

In these experiments it was necessary to arrange to deliver into the muscle the threshold portion of shocks of any strength. One of the arrangements that has been employed for this purpose may be described as follows: The terminals of the secondary coil were connected with the ends of a low resistance rheocord (32 ohms) and from this, by means of a sliding contact the amount of current that would give a threshold contraction of the muscle was led into the rest of the apparatus, which was as described in the section on general methods. The resistance of the bridge was made low so that the amount of current delivered to the muscle could be regulated without at the same time affecting to any appreciable extent the total secondary resistance.

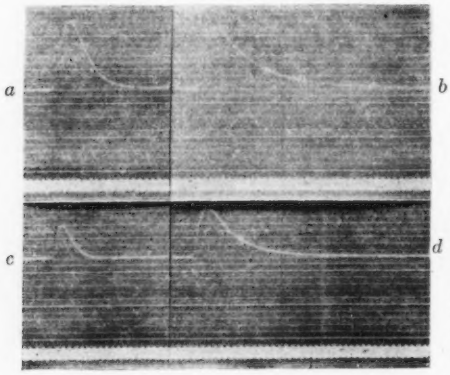


Fig. 15, *a*, *b*, *c* and *d*. Showing the effect of the strength of a shock upon its configuration and relative physiological efficiency. The records are described in Table XXI. The tuning fork is making 500 d. v. per second.

Figure 15, *a*, *b*, *c* and *d*, exemplifies the results obtained. The analysis of this figure is given in Table XXI. Considering only the extremes, it is seen that increasing the strength of the shock by approximating the coils increases very decidedly the duration of the recorded curve, from which it may be concluded that the

duration of the processes in the secondary coil is correspondingly increased.

The effect upon the recorded amplitude is not the same in the two cases. In the case of the slower of the two shocks, the break of coil 1, the stronger shock, *b*, is the lower, whereas in the case of the quicker of the two shocks, the break of coil 3, the stronger shock, *d*, is the higher. Usually the estimation of the true amplitude from the recorded amplitude is possibly only through an analysis by the gap method. That has not been done here. But, since the conditions here are simpler than is usually the case, it is possible to infer the real relative amplitude from the recorded amplitude. This can certainly be done in

TABLE XXI

Analysis of figure 15, a, b, c and d, illustrating the effect of strength of shocks upon their configuration and relative stimulating value

COIL	AT	SHOCK	FIGURE	FRACTION REQUIRED FOR THRESHOLD CONTRACTION	DEFLECTION		
					Amplitude	Time to maximum	Duration
				Denom. = 100	*mm.*	σ	σ
1	12.2	B	a	100.0	20.0	6.4	36.0
	0		b	18.2	18.2	6.5	70.0
3	11.1	B	c	100.0	9.5	3.4	19.4
	0		d	25.7	15.0	5.4	53.0

the case of the shocks from coil 1. Of two shocks of approximately the same real height, the quicker one will be reproduced by the galvanometer lower in amplitude than the slower. Here, as a matter of fact, the record of the quicker shock is a bit higher than that of the slower. Therefore, the stronger shock undoubtedly has the lower real amplitude. In the case of parts *c* and *d* of figure 15 the situation is not quite so simple. The increased height here produced by increasing the strength of the shock might well have been due to the associated lengthening of the shock, and in our opinion probably was. We may, therefore, conclude that the threshold fraction of a strong shock, in comparison with that of a weak shock, as indicated by these observations, is low in amplitude and long in duration.

Since the increase in the duration of the shock is here associated with a diminution in real height, it is impossible to determine by calculation which of the two shocks contains the larger amount of current. Observations which we have made with the aid of the ballistic galvanometer, however, show that the threshold fraction of the stronger shock determines by far the larger deflection. Here, therefore, in contradistinction to the result recorded below in connection with the subject of secondary resistance, the change in the form of the shock, due to an increase in its strength, does not prevent the associated increase in the amount of the current from manifesting itself; the threshold fraction of the slower (stronger) shock does not acquire the same amplitude as that of the quicker (weaker) shock.

These experiments, moreover, demonstrate that the increase in the efficiency of a shock as the coils are approximated, is not in proportion to the quantity of the contained current. For if it were, the amount of current contained in the threshold fractions, as meted out in these experiments, would have been the same at all strengths. Here, when the coils are approximated, the quantity of current in the shocks increases more rapidly than their physiological efficiency. This fact must be taken into consideration in attempting to assign physiological values to shocks ranging above the threshold. Calibrations based upon quantity of current do not indicate the correct relative differences in physiological efficiency. An indication of this is seen in the curves published by Wertheim-Salomonson (35); the curve based upon the quantity of current contained in the break shock increases somewhat more rapidly than the curve based upon Wertheim-Salomonson's method of physiological calibration.

Secondary resistance

Literature. It has been known for some time (36) that the resistance in the secondary circuit has an effect upon the physiological efficiency of induction shocks, increasing the resistance necessitating approximation of the coils to maintain the shocks at threshold value (37, 38). Upon varying the resistance in

the secondary circuit and then determining the fraction of the total induced current that is necessary to produce a contraction of a nerve muscle preparation, Gildemeister found that the amount of electricity necessary for a minimal stimulus varies inversely as the secondary resistance. As has been stated, Gildemeister (39), therefore, assumed that the resistance has an effect upon the configuration of the shocks.

Methods in general. In our study of the effect of secondary resistance, we first convinced ourselves of the correctness of Gildemeister's observations by exactly repeating his experiments. At the same time, the deflections of the string galvanometer produced by the shocks were recorded. We have not, however, made a systematic study of the effects of varying the resistance in shunt with the secondary coil upon the form of shocks because such shunt resistances are not employed in physiological investigations, except for the purpose of shunting out completely one or the other of the shocks. The effects of such complete shunts have been recorded in a preceding section. Subsequently a more direct method of attacking the problem, one more in accord with the conditions that obtain in physiological experimentation, was employed. The apparatus used was the same as that shown in figure 4. The resistance was inserted in the secondary circuit at the point H. In those experiments in which we desired to study the effects of a wide range of resistance, the resistance of the galvanometer shunt, R_2, was decreased to 129–200 ohms.

Effect of secondary resistance on the configuration of shocks. In the case of all shocks, increasing the resistance decreases the amplitude of the recorded deflections. This is clearly shown in Table XXII, column 6. In the table which has been compiled by selecting a few typical results, the decrease in the amplitude of the deflection is seen either as an actual decrease in the recorded amplitude when the resistance is increased while keeping constant the amount shunted into the galvanometer, or as an increase in the fraction of the current which it is necessary to shunt into the galvanometer in order to keep the amplitude of the deflection constant as the resistance is increased.

When the amplitude of these shocks is analyzed by the gap method it is seen that in the case of the slower shocks (makes of coils 2 and 3 and break of coil 1) the decrease in the amplitude determined by increasing the resistance is within the limit of error, correctly indicated by the galvanometric record of the

TABLE XXII

Showing the recorded and real relative amplitudes of shocks as affected by secondary resistance

1	2	3	4	5	6	7	8	9
				DEFLECTION				
	COIL	COIL SEPARATION	SHOCK	Shock		Gap		SECONDARY RESISTANCE
				Fraction used	Amplitude*	Maximum amplitude†	Fraction used	
		cm.		*Denom.* = 200	*mm.*	*mm.*	*Denom.* = 200	*ohms*
1	3	8.0	B	1.0	16.0	4.0	1.0	200
2				1.0	6.0	3.5	1.0	5,200
3				1.0	2.0		1.0	20,200
4				2.8	16.0	8.0	2.8	5,200
5				8.0	15.5	14.0	8.0	20,200
				Denom. = 2000			*Denom.* = 2000	
6	3	8.0	M	35.0	14.0	2.0	35.0	129
7				63.0	14.0	2.0	63.0	2,129
8				164.0	14.0	2.0	164.0	5,129
9	2	5.2	M	27.0	15.0	8.0	3 × 27	129
10				130.0	15.0	8.0	3 × 130	2,129
11				319.0	15.0	8.0	3 × 319	5,129
12	1	9.2	B	20.0	14.0	7.0	3 × 20	229
13				20.0	3.5	2.0	3 × 20	2,229
14				20.0	2.0–	1.0	3 × 20	5,229

* Magnification 500 diameters.

† The highest of the whole series, and therefore the one that includes the crest of the shock. It is a measure of the amplitude of the full shock. Magnification 1000 diameters.

full shock; the recorded amplitude (column 6) of any one shock under different resistances is proportional to the true potential amplitude as determined by the gap method (column 7).

This, however, is not true in the case of the quicker shocks (the break of coil 3). Here it is seen that the gap amplitude

decreases much more slowly with increasing resistance than does the amplitude of the full shock; and that when the recorded amplitude is kept constant by shunting more of the current into the galvanometer, the gap amplitude actually increases as the resistance increases. Such a result as this can mean one thing only, namely, that increasing the secondary resistance increases the potential gradients of a shock.

This inference is completely confirmed by a further analysis of the shocks by the gap method. In order to make the results obtained in this analysis exactly comparable, the gap brush was fixed in the desired position, and then the amplitude of the gap deflection of one and the same shock under different resistances was read. By making readings with the gap brush in a sufficient number of positions the relative rate of rise and fall of the potential in the same shock, but under different resistances, could be determined.

Some of the results thus obtained have been collected in the form of curves (fig. 9, *a*, *b* and *c*). The interpretation of these curves is complicated somewhat by the difficulty of obtaining for comparison, shocks of exactly the same real amplitude. Despite this difficulty and despite some irregularities in the case of the curves of the break of coil 1, it is evident that the effect of increasing the resistance is to shorten the time to maximum and to hasten the subsequent fall of potential. The quantity of current contained in shocks of the same amplitudes diminishes as the resistance increases. This is true of both the make and the break shocks.

Relation of secondary resistance to physiological efficiency of shocks. With this information with regard to the effect of secondary resistance upon the form and amplitude of shocks at our disposal, the next step was to determine the effect of secondary resistance upon the stimulating value of shocks as expressed in terms of their real amplitudes. It has been seen that the recorded and real amplitudes of a shock are reduced by increasing the secondary resistance; in order to maintain them at a constant amplitude, the coils must be considerably approximated. Likewise, when these shocks are used to stimulate a muscle, it is

found that in order to maintain them at threshold value as the secondary resistance increases the coils must be approximated. When the amplitude of threshold shocks is determined by means of the gap method it is found (see Table XXIII), that in the case of one and the same shock, increasing the resistance lowers very slightly the threshold amplitude. This effect, though, is so slight as to fall almost within the limits of experimental error. If, however, it can be substantiated, it would indicate that for

TABLE XXIII

Showing the effect of secondary resistance on the threshold position of the secondary coil and on the real relative amplitude of the shocks as determined by the gap method

COIL	SHOCK	THRESHOLD SEPARATION OF COILS	MAXIMUM GAP	FRACTION USED	SECONDARY RESISTANCE
		cm.	*mm.*	*denom.= 2000*	*ohms*
3	B	14.50	3–4	100	129
		13.80	4		2,129
		13.30	4–		5,129
		12.70	3		10,129
3	M	9.25	8–10	400	129
		7.55	8		2,129
		5.50			5,129
		2.40	7–8		10,129
3	B	11.80	20–22	220	129
		11.40			2,129
		11.10			5,129
		10.70	18–20		10,129
1	B	11.50	14–16	220	129
		6.00	15		2,129
		0.30	12–14		4,129

physiological efficiency, the steeper gradients determined by the higher resistances more than counterbalance the effect of the associated decrease in the quantity of the contained current.

Discussion of the significance of Part I in relation to the physical calibration of coils for physiological purposes. In summarizing the results of the foregoing sections dealing with the configuration of shocks from different coils and as influenced by the variable conditions commonly met with in physiological experimentation, it is merely necessary to direct attention to the fact that

the form of shocks is subject to manifold variations. At least three factors play a part in determining the physiological efficiency of shocks as measured by threshold stimuli, namely, the amount of the contained current, the current gradients and the amplitude. The configuration of shocks from different coils may be so different and in the case of the same coil, may be so changed by the distance between the primary and secondary coils, by the secondary resistance and perhaps by other conditions still unknown, as to cause all three factors to vary to some extent independently of each other. Furthermore, it is more than likely that each factor will be found to manifest its own effect in different ways upon different tissues, so that the results we have obtained in experiments with muscle may be found to be inapplicable, without some modification, to other tissues. Indeed, it may be found that different physiological states of the same tissue will alter the relative efficiency of these factors. It is very evident that further work is necessary to determine the significance of these questions.

In the meantime it is necessary to call attention to the bearing of our results upon the calibration of coils for physiological purposes by physical methods. Obviously only those shocks would certainly be equal physiologically that could be exactly superimposed. The string galvanometer affords a means of thus comparing the shocks. For even though it is not quick enough to indicate correctly the true form of a shock, it is merely necessary to deliver to the galvanometer simultaneously and in opposite directions the two shocks to be compared, when only those shocks that can thus be exactly superimposed will cause no deflection. The validity of such a method of comparison is self-evident. Nevertheless, it can do no harm to cite just one of our attempts to balance against each other in the string galvanometer shocks containing equal quantities of current from two different coils. Coils 1 and 2 were first connected together through a ballistic galvanometer in the way that is usual in making a comparative calibration, and the secondary coils were adjusted so that the opposing shocks exactly neutralized each other, or, when taken separately, gave equal deflections in opposite directions. Then

these shocks were delivered in opposite directions, first successively and then simultaneously, to a string galvanometer. The results, given in Table XXIV, clearly bear out the premises and show that these shocks summed algebraically in the string galvanometer do produce a complex deflection that might have been determined by calculation from a knowledge of their forms taken separately.

Obviously the all important precaution to observe in order to obtain induction shocks of the same configuration, and therefore of the same value physiologically, is in constructing coils, to

TABLE XXIV

Giving the results of an attempt to balance against each other two shocks of different form

COIL	SEPARATION OF COILS	SHOCK	D'ARSONVAL DEFLECTION	STRING DEFLECTION	FRACTION USED
	cm.		*mm.*	*mm.*	*denom. = 51000*
1	4.15	B	+32.0	+ 8.0	27
2	0	B	−31.0	−14.5	27
1	4.00	B	±0	+ 3.0 2nd	27
2	0	B combined		− 9.0 1st	
1	4.00	M	+30.0	+ 8.0	50
2	0	M	−31.0	−11.0	50
1	4.00	M	±0	+ 2.0 2nd	50
2	0	M combined		− 5.0 1st	

adhere rigidly to a fixed standard. Even then, unless the extraneous conditions are kept constant, the value of the shocks might vary in ways beyond the control of the experimenter. If, for example, we were stimulating a muscle that offered a known resistance, this resistance might vary in the course of an experiment, indeed, it has been stated that the resistance of muscle is different in the relaxed and in the contracted state. Evidently it would be very difficult to so adjust extraneous conditions under such circumstances so as to maintain an exact similarity of shocks. We have, however, no clear conception of the real significance of these difficulties; it is a matter for future work to determine.

PART II. REPEATED SHOCKS

In physiological experimentation it is frequently necessary to employ rapidly repeated stimuli. The rates commonly employed range from 10 to 100 per second, while for special purposes rates exceeding even 1000 per second have been used. Induction coils are commonly employed to furnish the stimuli, and use is made sometimes, of both the make and the break shocks, either unmodified or equalized by the Helmholtz arrangement, and sometimes of the break shock alone, the make then being presumably short-circuited out.

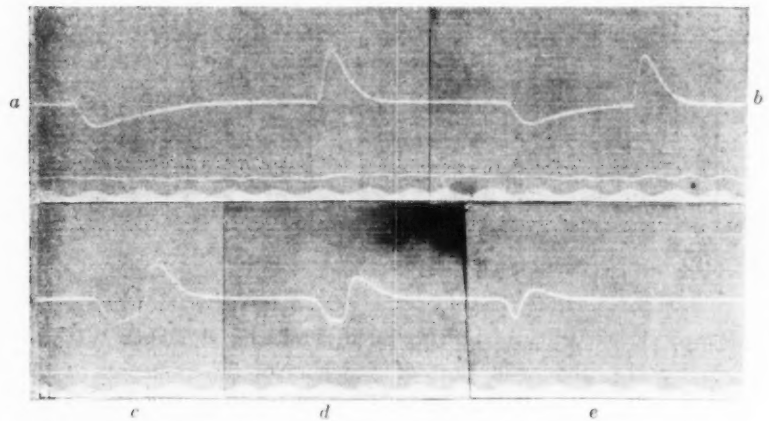


Fig. 16. Showing the make-break couples analyzed in the second part of Table XXV. Each double vibration of the tuning fork = 0.01 σ.

We have studied repeated induction shocks delivered in the three ways above mentioned with the object of determining whether repetition at these rates affects their amplitude and their value as stimuli.

Make-break and break-make couples. A simple method of determining whether the rapid succession of induction shocks modifies the form of the shocks is to obtain records of make and break shocks, or of break and make shocks in pairs with different time

intervals between the members of the couples. This is easily accomplished by means of the make-break and break-make rotary interrupters. If the data relative to the form and duration of shocks, collected in the preceding sections of this paper are correct, it should be possible to predict the result of an analysis made by the present method, since if the two shocks should

TABLE XXV

Giving an analysis of records of make-break couples obtained with the string galvanometer

COIL*	M-B INTERVAL	AMPLITUDE		BREAK BEGINS BELOW ZERO	DURATION OF B
		M	B†		
	σ	*mm.*	*mm.*	*mm.*	σ
2	21.60	4.7	14.6	0.+	10.9
	7.45	4.7	10.0	2.5	10.2
	4.00	4.7	6.5	4.5	9.8
	2.10	4.5	3.1	4.5	10.2
1‡	53.0	7.2	16.5	0.0	17.8
	27.0	6.8	14.2	1.0	18.5
	15.0	7.2	10.0	4.0	17.5
	6.4	7.0	6.0	6.0	17.5
	2.7	6.5	3.0	5.5	16.5

* The position of the coil is constant.

† Measured from zero level.

‡ See figure 16.

overlap, the amplitude of the records of the shocks would be given by the algebraic sum of the shocks taken separately.[30] That this is the case our records clearly demonstrate (see fig. 16 and Table XXV). It will be noted, for example, that when the break shock begins to fall into the period of a preceding make

[30] Two factors, in addition to those mentioned in the section on the interpretation of galvanometric records, play a part here in pulling down the amplitude of the record of the second shock of these couples, namely (a) the position of the string at the instant that shock starts, and (b) the amount of current which still remains in the first shock at that moment, and which must be neutralized by the second shock. If the string galvanometer followed accurately the contour of the shocks, the second factor alone would be operative. There are very good reasons for believing, however, that the first factor is relatively insignificant; this is indicated clearly by the effect of the overlapping upon the threshold position of the coil (see below) and also by a few observations we have made with the aid of the gap method.

shock, its amplitude is immediately reduced, whilst the recorded, and therefore the real duration of the break shock, as well as its general form, are perfectly preserved. Furthermore, in accordance with theory we have found that the quantity of current in each of the two members of any one couple remains the same, for the ballistic galvanometer is not deflected by any of the couples.

Entirely comparable results are obtained in experiments in which the break is made to precede the make.

TABLE XXVI

Giving an analysis of the threshold make-break couples shown in figure 17, a to f

1	2	3	4	5
FIG. 17	M-B INTERVAL	THRESHOLD SEPARATION OF COILS	DEFLECTION AMPLITUDE	
			M	B
	σ	*cm.*	*mm.*	*mm.*
a	65.0	16.15	0	11.0
b	24.0	15.00++	1.0+	11.0
c	13.0	14.70	4.5	10.0
d	9.0	13.70	8.0	9.0+
e	6.0−	12.85	11.0	8.5
f	2-3.0	11.00	14.5−	6.5

Physiological effects of fusion of make and break and of break and make shocks

Effect on their value as stimuli. The simplest method of ascertaining whether the overlapping of the shocks of a couple affects the value of the couple as a stimulus, is to determine the threshold position of the secondary coil and the consequent deflections of the string as the break is made to encroach more and more upon the make. The results of a typical experiment in which the frog's gastrocnemius muscle was stimulated with coil 1 are given in figure 17, *a* to *f*, of which Table XXVI is an analysis. As might have been predicted, with increasing overlapping it becomes necessary, in order to obtain a contraction, to bring the coils closer and closer together. This begins when the make-

break interval has approximately the duration of the make shock, which in this case is somewhat less than 64.0 σ,[31] and continues as far as the experiment has been carried, in this case to a make-break interval of about 1.0 σ. Furthermore it can be seen in the table that despite the approximation of the coils that is necessary to lift the stimulus to the threshold as the make-break

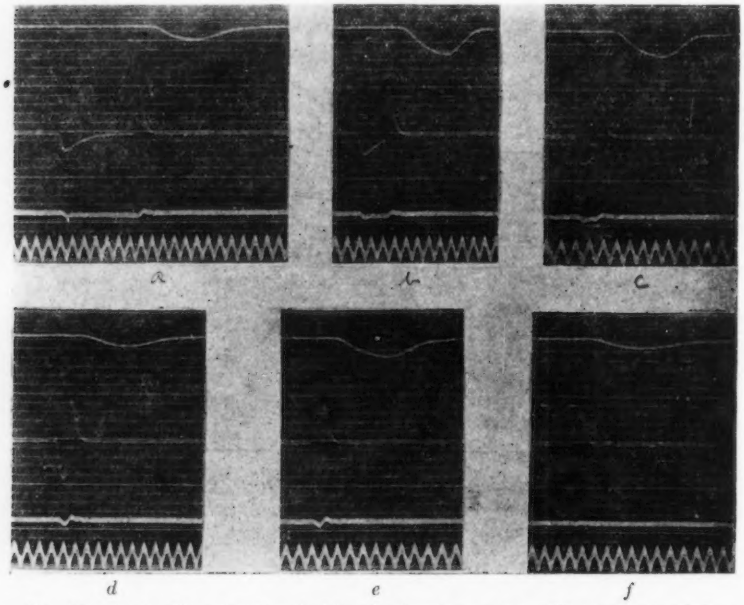


Fig. 17, *a* to *f*. Showing threshold make-break couples. The analysis of these couples is given in Table XXVI. From above downward the tracings are of the muscle, the string, the signal, and the time in hundredths of a second.

interval is shortened, the amplitude of the break above the zero level actually diminishes. We are inclined to believe, however, that this decrease, in the early part of the experiment, at least,

[31] The secondary resistance in this experiment was rather low, roughly 1129 ohms, a fact that probably explains in part, at least, the unusually long duration of the make shock. That this is not due to instrumental error is proved by the change in the threshold of the muscle.

is in large part apparent and not real, and due to the increasing distance the string must travel when the break begins, in order to attain its crest. We are led to this view by the fact that the ratio:

$$\frac{\text{Distance of beginning of break shock below zero}}{\text{Decrease in height of break above zero}}$$ tends to remain constant

$$\left(\frac{2.5}{.5}(5) = \frac{4.5}{1}(4.5) = \frac{8}{2}(4) = \frac{11}{2.5}(4.4) = \frac{14.5}{3.5}(4.1)\right).$$

The amplitude of the make shock, on the other hand, increases tremendously as the coils are approximated. The recorded increase naturally must continue *pari passu* with the approximation of the coils until the make-break interval becomes less than the recorded time to maximum of the make shock, which here is 6.5 σ. The real increase must, however, continue beyond this point and until the make-break interval becomes less than the real time to maximum, which the gap method has shown to be not longer than 2.2 σ.

It is scarcely necessary to add that these figures apply only to the coil 1 under the conditions here obtaining. The figures obtained with coil 3 are, however, quite similar since the make shocks of these two coils have approximately the same duration; whilst with coil 2 the make-break interval must be made very much smaller if comparable results are to be obtained.

Interchange of effectiveness of shocks. It occurred to us that the increase in the height of the make shock seen in these experiments, together with the simultaneous decrease in the height of the break shock, which we thought might, at least in part, be real, might result at a certain stage of the experiment in a reversal of the relative physiological efficiency of the two shocks, so that the make shock would usurp the place of the break shock as the stimulus.

The approximate time at which this reversal should occur can be arrived at through theoretical considerations. It has been said that as the make-break interval is shortened, the make

and break shocks continue to contain the identical quantities of current. It has also been seen that with this overlapping there is no appreciable change in the recorded duration of the break shock, an observation which may be taken to mean that there is no marked change in the real duration of the break shock. Whether or not this remains true when the make-break interval becomes very small we have not determined, but with this we are not now concerned. If the part of the make preceding the break had the same form as the break shock, it is obvious that the true amplitude of the make shock would become equal to that of the break shock when the make-break interval became equal to the duration of the break. Otherwise the two shocks would not contain the same quantity of current. As a matter of fact, however, the full break and the anterior part of the make have not the same configuration, the curved side of the former being concave, of the latter, convex; whilst the apex of the break is more acute than that of the make. A fraction of the make of the same base and amplitude as the full break would, therefore, contain by far the larger quantity of current. Obviously, therefore, as the break encroaches upon the make the two will not attain equal amplitudes, and approximately equal stimulating values, until the make-break interval becomes considerably less than the duration of the break shock. We realize that the problem is considerably more complex than this categorical presentation would lead one to believe. It would, however, scarcely be profitable to enter into a discussion of anything more than the essential considerations at this time.

The following experiment, Table XXVII, in which the shocks were analyzed by the gap method, is cited for the purpose of showing that at a certain stage in these make-break experiments the make shock actually does surpass the break shock in amplitude in accordance with the foregoing theoretical considerations. When stimulating with threshold make-break couples from coil 3, it is seen (Table XXVII), that the make shock, as indicated by the maximum gap, surpasses the break shock in amplitude some time before the make-break interval reaches $0.744\ \sigma$ in duration; whilst in the case of coil 2, this occurs shortly after

the duration of the make-break interval becomes less than 0.665 σ. When these figures are compared with the durations of the break shocks, namely, 2.42 σ and 1.675 σ, of coils 3 and 2, respectively, it is seen that experiment bears out the theoretical considerations as well as could be expected.

The fact as seen in Table XXVII, that at a certain stage of this experiment the real amplitude of the make shock becomes greater than that of the break, furthermore furnishes strong presumptive evidence that the make shock somewhere in the vicinity of that stage is supplying the stimulus.

TABLE XXVII

Giving the essentials of a gap experiment in which the gastrocnemius muscle was stimulated by M-B couples. The secondary resistance is 2129 ohms. Speed of discs, 100 revolutions in 6.2 seconds with coil 3, and 100 revolutions in 7 seconds with coil 2; the gap, therefore equals 0.124 σ and 0.14 σ, respectively

COIL.	THRESHOLD SEPARATION OF COILS	M-B INTERVAL	RECORDED AMPLITUDE OF SHOCKS. MAGNIFICATION = 500 DIAMETERS		AMPLITUDE OF MAXIMUM GAP. MAGNIFICATION = 1000 DIAMETERS		AMPERAGE IN PRIMARY CIRCUIT
			M	B	M	B	
	cm.	σ	*mm.*	*mm.*	*mm.*	*mm.*	
3	13.70	10.788	5	13	1–	8	0.5
3	4.30	0.744	15+*	6	12	6	0.5
2	5.15	0.910	12	18	6	16	0.5
2	2.27	0.665	24	16–18	12	16	0.5
2	–0†	0.420	14	10	14	7	0.6
2	1.80	0.420	14	10	22	11	1.8

* Out of field.
† Still below threshold.

Further presumptive evidence in favor of this conclusion has been obtained by another method of procedure. It can be shown that at a certain stage in these experiments with make-break couples, short-circuiting out the break shock does not alter the threshold position of the coil, thus indicating that the make has been stimulating. The essentials of an experiment of this kind, made with coil 1, are given in Table XXVIII.

The logic of this experiment is clear: A make-break interval is found (observation 3) that stimulates the muscle only when the secondary coil is somewhat closer to the primary than is

necessary to produce a threshold contraction with the make shock alone (observation 6). It is then found that short-circuiting the break shock of the No. 3 couple (controlled in the mutostat) does not alter the threshold position of the coil (observation 4). This analysis therefore again leads to the conclusion that when the make-break interval becomes sufficiently small, in this case, 1.8 σ,[32] though the exact limits have not been determined, the make shock, instead of the break shock, may stimulate.

If there is a stage in these experiments at which the make usurps the place of the break as the stimulus, then, since induction shocks always stimulate from the cathode and since the make and break currents flow in opposite directions, it should

TABLE XXVIII

Giving the essentials of an experiment proving that the make of a make-break couple may become more efficient than the break. Coil 1

KIND OF STIMULUS	THRESHOLD SEPARATION OF COILS
	cm.
(1) M-B interval greater than 17.9 σ	17.6
(2) Same as (1), but breaks short-circuited out	14.1
(3) M-B interval 1.8 σ	13.2
(4) Same as (3), but breaks short-circuited out	13.2
(5) Simple break	17.2
(6) Simple make	13.9

be possible to demonstrate the change in the character of the stimulus by a change of the pole from which the stimulus starts. This has been successfully accomplished in several ways of which we shall instance only one here (Table XXIX).

The turtle's heart is brought to a standstill by the first ligature of Stannius. Platinum needle electrodes are then fastened to it, one to the auricle, the other to the ventricle. Then, by stimulating with single break and single make shocks (coil 1) in each trial first in one direction through the preparation, and

[32] It will be noted that in accordance with theory this time is considerably shorter than the duration of this shock, and that it is longer than the corresponding values obtained with coils 2 and 3.

then in the other, it is determined whether the polar effects can be brought out, a matter that depends upon the relative irritability of the auricle and of the ventricle. In case they are demonstrable, the sequence with which the auricles and the ventricles of the heart respond to a long and then to a short make-break couple is determined. Such experiments have shown conclusively that the change of direction of the beat does take place with the change from a long to a short make-break interval (compare the last four observations with those preceding them).

The attempt has also been made to determine whether there is, at some stage in the progressive shortening of the make-break

TABLE XXIX

Showing a change in direction of the beat of the turtle's heart when a make-break couple is made sufficiently short

KIND OF SHOCK	DIRECTION OF CURRENT*	THRESHOLD SEPARATION OF COILS	PART OF HEART TO CONTRACT FIRST
		cm.	
Single break	L	15.5	V
Single break	R	15.6	A
Single make	L	12.8	A
Single make	R	12.7	V
M-B scarcely overlap	L	15.7	V
M-B scarcely overlap	R	15.8	A
M-B interval 1.8 σ	L	7.65	A
M-B interval 1.8 σ	R	6.6	V

* L and R designate the position of the commutator in the secondary circuit. The current direction through the heart when the commutator is turned, e.g., to the left (L) is, with the break shock, the same as when it is turned to the right (R) with the make shock.

interval, a change in the latent period of the contraction of a skeletal muscle, stimulated directly. Theoretically the latent period should suddenly shorten if at any stage the make instead of the break should become the stimulus. The make-break periods, however, at which the shifting presumably occurs are so short, lying as they do in the vicinity of 1.0 σ, that by this method it is difficult, owing to the gradual rise of the muscle curve, to measure the records with a degree of accuracy that is sufficient for these purposes. In view of this difficulty we feel justified in

saying only that the evidence obtained through measurement of the latent period is not opposed to the possibility of an interchange of the physiological efficiency of the make and break shocks when the make-break interval becomes sufficiently short.

Break-make couples. The few observations we have made on the effects of make following break have brought out little more than might have been predicted from our knowledge of the duration of the shocks. The results of one experiment with coil 1 are given here in tabular form (Table XXX). It is seen that in this case the efficiency of the break shock, as determined by the threshold position of the coil is not reduced until the break-

TABLE XXX

Showing the changes in the threshold and in the string deflection resulting from progressive shortening of the break-make intervals. Coil 1

OBSERVATION NUMBER	B-M INTERVAL	THRESHOLD SEPARATION OF COILS	DEFLECTION AMPLITUDE	
			B	M
	σ	*cm.*	*mm.*	*mm.*
1	30.0	15.0	20	7+
2	20.0	15.0	20	8
3	13.0	15.0	20	7+
4	8.0	15.0	20	6+
5	4.0	15.0	20	5
6	somewhat shorter*	14.5	18	3+
7	somewhat shorter	13.5	14	3
8	somewhat shorter	12.6	14	3
9	somewhat shorter	13.4	14	3

* With the apparatus used in this experiment, these short intervals could not be accurately measured. In the last observation the interval was probably considerably less than 1.0 σ.

make interval becomes less than 4.0 σ. The string deflections with the shorter break-make intervals signify little since the upward motion of the break deflection is cut short by the make before the string has had time to indicate the full potential of the break. Following a break shock with a make shock is in effect the same as aftershortening the break shock; and the break-make interval at which the efficiency of the stimulus begins to diminish (somewhere below 4.0 σ) agrees with the particular

aftershortening that begins to reduce the efficiency of the same shock (1.5 to 2.5 σ). It is obvious, therefore, that the change in threshold value seen when the break-make interval becomes sufficiently small, is attributable mainly, if not exclusively, to processes going on within the circuit rather than within the tissues.

Discussion. v. Kries and Sewall (40), in 1881, studied the effect on the response of muscle of applying in rapid succession two equal submaximal induction shocks of opposite sign. They came to the conclusion that "there is a value below which the interval between the two shocks in opposite directions may not sink if summation of their action is still to be obtained; below this value there occurs a subtraction instead of summation." In the case of curarized muscle they found this interval to be very small indeed; it lay approximately between 3.0 and 1.0 σ. "Nevertheless," they say, "it is large enough to preclude as an explanation of the result the simple physical neutralization of the shocks." In the light of the results obtained in the foregoing experiments, however, the explanation which v. Kries and Sewall have discarded would seem to be the very one that satisfactorily accounts for their observations. Although our break-make couples are not identical with the couples employed by v. Kries and Sewall, there can be no doubt that both were, in effect, the same; and the intervals between shocks at which, in our experiments, the couples begin to diminish in efficiency agrees very well with the range determined by v. Kries and Sewall. As our results are perfectly explicable on the basis of physical neutralization, there can be no reason for holding any longer to a physiological explanation of the phenomenon.

Tetanic stimulation

The effect of the rate of interruption on stimulating value. It follows from the results of the preceding sections that when the primary current is regularly interrupted, and so that the make and break shocks are equally spaced,[33] the break shock will

[33] For the sake of convenience we shall consider only the case of equally spaced shocks; the effects of other spacings can easily be determined by calculation.

suffer a diminution in amplitude and effectiveness when the interval between shocks becomes smaller than the duration of the make shock.[34] Using the durations given in Table VII as a basis for calculation, the effectiveness of the break shocks should begin to suffer a reduction when the rate per second of break shocks begins to exceed 16.7, 65.0 and 15.7 for coils 1, 2 and 3, respectively. It should be added that the results thus obtained are, of course, applicable only to the particular conditions under which these estimations of the durations have been made.

We have not supplied ourselves with apparatus that is sufficiently exact to permit of a quantitative experimental demonstration of these conclusions; we have, however, made some qualitative observations with the aid of the notched rotary interrupter that are suggestive of their essential correctness. This apparatus is deficient for this purpose in that the spacings are not perfectly uniform and in that the make period is somewhat longer than the break period. Furthermore, in order to increase the rate of interruption with this apparatus, it is necessary to increase the speed of rotation of the disc, and this in turn modifies the contacts, and consequently the physiological efficiency of the shocks induced. Altogether, therefore, the method has been crude and only the roughest kind of an approximation of the facts could have been expected to come of it.

The rates of interruption at which the stimuli in our experiments showed an appreciable diminution in effectiveness, calculated on the basis of equal spacing of the make and break shocks, were 30.2, 54.0 and 34.7 breaks per second for coils 1, 2 and 3, respectively; at these rates it became necessary to approximate the coils in order to maintain the stimulus at the threshold value. Although these results differ rather widely from the theoretical values, they, nevertheless, show the same relative variations: the rates at which coils 1 and 3 begin to show a decrease in efficiency are practically alike, and both of these are in turn much slower than the critical rate of coil 2. The results also

[34] This may be designated the critical rate.

direct attention to the comparatively slow rates of interruption at which, owing to the overlapping of shocks, tetanic stimulation suffers a reduction in efficiency. They also indicate that any change in the spacing of the make and break shocks, when the interruption exceeds the critical rate, will alter the physiological efficiency of the stimulus. Such changes are bound to occur not only whenever the rate of interruption is changed, but also whenever a variation is made in the adjustment of any of the vibrating interrupters, such as Neef's hammer or the tuning fork, commonly employed in the physiological laboratory.

Discussion. The literature of this subject contains rare references to the possibility of modification of physiological effects by the overlapping of rapidly repeated induction shocks, but physiologists, at least, refer to this possibility mainly, if not solely, for the purpose of excluding it (40). Jones (41) alone clearly recognizes the possibility of such overlapping at even moderate rates of stimulation, but takes no account of its real significance. This is all the more remarkable when it is recalled that the published values of the duration of induction shocks (see Table IV) are such as should have attracted attention to the fact that there is a finite limiting rate of interruption beyond which overlapping and consequent neutralization of current must occur. Thus, if we accept Bernstein's value of the duration of the make shock, namely 3.3 σ, it is seen that evenly spaced shocks would begin to suffer some neutralization when the break shocks began to recur at a rate that exceeded 151.5 per second.

Some investigators have found it necessary, when stimulating with shocks supplied at increasing, though still moderate, rates, to approximate the coils, or to otherwise increase the strength of the stimulus, in order to obtain contractions.[35] So far as we have been able to determine, however, they either take no notice whatever of this fact, or it is explained upon the basis of some physiological phenomenon. By way of illustration we may refer to the work of Beritoff (23). It is seen everywhere in his lengthy paper that with the more rapid rates of interruption, the coils

[35] See, for example, Roth (42) and Beritoff (23).

are always closer together. This he explains by assuming that with the more rapid rates the stimuli follow one another so rapidly that they fall into the relatively refractory phases of the preceding contractions. It is quite possible that this explanation has a measure of truth in it; in our experiments, however, it must be a relatively insignificant factor, for with different coils we have found the critical rates of stimulation to be very different. If the refractory phase were the main factor in reducing the value of rapidly recurring stimuli, the reduction would have occurred at approximately the same rate of interruption irrespective of the coil furnishing the shocks.

In passing we wish to direct attention to a conclusion that follows obviously from the results obtained in our study of make-break couples, namely, that as the rate of interruption increases beyond the critical point, the make and break shocks will tend, for a time at least, to become more nearly alike physiologically. We have not as yet had the opportunity of determining experimentally the exact significance of this tendency.

Effect of short-circuiting out the make shocks

Effect on the critical rate. Short-circuiting out the make shocks during repeated stimulation naturally will not modify the break shock, and through that the physiological efficiency of it as a stimulus, until the make shock begins to encroach upon the break. Since, however, short-circuiting the secondary coil prolongs the process of induction, it is obvious that the critical rate of shocks, by which is meant the rate at which overlapping begins, will be lower when the attempt is made to short-circuit out the make than when the shocks are permitted to run their course unmodified. All this is easily demonstrable qualitatively, though we have not attempted to determine experimentally the exact significance of this factor. It is obvious, however, from what has been said with regard to the duration of foreshortened make shocks, that with the secondary coil at 0, for instance, the critical point may be attained when the slow rate of 7.7 break shocks per second is reached.

But aside from this it is actually impossible to completely short-circuit out a make shock when the interruption is faster than the critical rate. For the short circuit must cease at least an instant before the primary current is broken. A foreshortened make shock will, therefore, result, and will last until the residual make potential is neutralized by the rising potential of the break. Indeed, when the rate of interruption is rapid enough to cause the break shocks to start well up in the make shock, the string galvanometer may still be deflected momentarily in the direction of the make even when the short circuit does not open until a perceptible interval has elapsed[36] after breaking the primary current. Evidently the deflection to the break side of zero potential cannot occur until the residual potential on the make side has been neutralized.

Ordinarily the make shock is short-circuited out by closing a shunt around the secondary coil a moment before the primary current is made, and then opening this shunt a moment before the primary current is broken. But when shocks are recurring at or beyond the critical rate the make shock has not completely run its course before the break appears. Therefore, in accordance with the foregoing discussion, there will result, under these circumstances, a foreshortened make, the amplitude of which will be greater than that of the corresponding part of the full make. In view of the fact that a shortened single make shock may, in the case of certain of the coils, have a higher physiological efficiency than the corresponding break shock, it seemed worth our while to determine whether, when stimulating tetanically beyond the critical rate, the escaping foreshortened make shock might not become more efficient than the break shocks which in this case also suffer some reduction in amplitude as a result of the overlapping.

Experiments of the following types, with coil 1, show clearly that this can actually occur:

1. A muscle was stimulated tetanically with full make and break shocks approximately equally spaced. When the rate of

[36] Quantitative estimations have not been made.

interruption was 35 breaks per second, approximately, a threshold contraction was obtained when the secondary coil was 10.9 cm. When the rate was increased to 69 breaks per second it was found that the threshold position of the coil became 9.7 cm: the interruption, presumably, was now well beyond the critical rate. The make was then short-circuited out in the usual way. At once, the height of the contraction increased tremendously and it was found that in order to reduce it to the threshold, it was necessary to move the secondary coil out to 13.2 cm., that is, beyond the threshold position for the unmodified shocks.

2. The results of a second type of experiment with coil 1 are given in Table XXXI. Comment upon these results is quite unnecessary.

TABLE XXXI

Showing that during tetanic stimulation with the makes and breaks faster than the critical rate, "short-circuiting out the make" may greatly increase the strength of the stimulus

STIMULUS	SEPARATION OF COILS	CONTRACTION
	cm.	
(1) Full makes and breaks at the rate of 91 breaks per second	11.45	Threshold
(2) Makes short-circuited	11.45	Maximal (?)
(3) Both makes and breaks short-circuited, leaving as nearly as possible only the gap intervening between the end of the make short circuit and the beginning of the break	11.45	Maximal (?)
(4) Same as 2	13.80	Threshold
(5) Same as 3	13.30	Threshold

We cannot be certain that we have succeeded in demonstrating a similar phenomenon with coils 2 and 3.

At this place we may refer to another type of experiment which demonstrates that during tetanic stimulation above the critical rate foreshortened makes may not only be more efficient than the breaks, but more efficient even than foreshortened breaks. A single experiment may be given in detail to illustrate the methods used and the results obtained (see fig. 18).

The primary circuit of coil 1 was interrupted by a tuning fork vibrating at the rate of 50 d. v. per second, and the notched

rotary interrupter was arranged to short-circuit out about 10.0 σ in about each 20.0 σ. These short circuits were made to recur at a rate that was either a trifle faster or a trifle slower than the rate of vibration of the fork so that the resulting asynchrony gave rise to "beats." A complete "beat" may be described as beginning with a short circuit which opens at such a time as to let through, say the terminal portion of the break shock; the upward deflection of this break is cut short almost immediately by a make shock which will be aftershortened somewhere on its ascending limb. The short circuit will end to let through, we will say, more of the succeeding break, while the next make will be aftershortened somewhat earlier than the preceding make and so on, the result being makes and breaks with progressively changing aftershortenings and foreshortenings until the state of

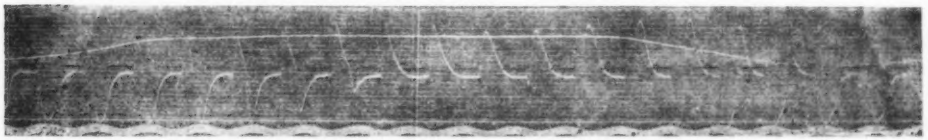


Fig. 18. Showing one "beat" as described in the text. The records from above downward are of the muscle lever (motion downward indicating shortening), the string, the signal and the tuning fork making 50 d. v. per second. This fork is also interrupting the primary circuit. The lines drawn on the record indicate approximately the periods of short circuit, and the letters *M* and *B*, the points at which the primary circuit was made or broken.

affairs existing at the beginning of the "beat" recurs, the length of a beat depending upon the degree of asynchrony of the tuning fork and the recurring short circuit. By these means it is possible to obtain in a comprehensive way all degrees of foreshortening and aftershortening of rapid rhythmical makes and breaks. When a muscle is stimulated with these "beats" and the secondary coil is withdrawn until the stimulus just exceeds the threshold, it is found that the muscle gives one short tetanic contraction in each "beat" (see fig. 18). This contraction begins when the foreshortened makes appear, that is to say, at a time

when the arrangement would compare with the state of affairs obtaining in an experiment in which the "makes were being short-circuited out." The advent of the first parts of the break shock does not increase the height of contraction; indeed the contraction dies away when the short circuit begins to encroach upon the breaks and to foreshorten them, and despite the fact that at this time the recorded amplitude, and probably also the real amplitude, of the break shocks is increasing. It is very probable, therefore, that in this experiment, too, the shocks of the highest efficiency are the foreshortened makes.

A similar experiment with coil 2 did not yield clear results. Although the muscle contracted for a short period in each beat, it so happened that during this period there were both breaks and foreshortened makes and it was therefore impossible to determine which were causing the contractions.

Deflections of the ballistic galvanometer by rapidly repeated shocks while short-circuiting the make. In the experiment preliminary to this investigation it was shown qualitatively that when the rate of interruption of the primary circuit is gradually increased while "short-circuiting out the make" induced currents, the deflection of a ballistic galvanometer connected in series with the secondary coil at first increases and then decreases. Here the results of a quantitative experiment may be given in which the deflection produced by coils 1 and 2 have been measured under similar conditions. It is seen in the curves (fig. 19) that at first, in accordance with expectation, the deflection of the ballistic galvanometer is proportional to the number of shocks delivered to the galvanometer. This simple proportionality, however, soon ceases to hold, while eventually an inverse relation between the rate of shocks and the deflection of the galvanometer comes to pass. As might have been predicted, these changes all occur earlier in the case of coil 2 than in the case of coil 1. Whether or not in experiments of this kind the deflection will eventually become negative, depends mainly upon the rate of interruption reached, and upon the situation of the short circuit; it is obvious that the nearer to the break the short circuit terminates, the more rapid must the rate of interruption become in order to obtain a negative deflection.

The uncorrected deflections of the string galvanometer, occurring in connection with these observations (plotted in fig. 19). when due allowance is made for instrumental error, explain fully the behavior of the ballistic galvanometer.

Initial contractions. In 1871 Bernstein (43) found that when a nerve-muscle preparation is stimulated with rapidly repeated shocks, an "initial contraction" alone might be obtained. In these experiments he used a coreless coil and a Helmholtz shunt in the primary, so as to obtain makes and breaks as nearly alike as possible. In order to assure himself that the initial contraction was not due to physiological causes, he repeated the experiment, substituting a multiplicator for the nerve-muscle prepara-

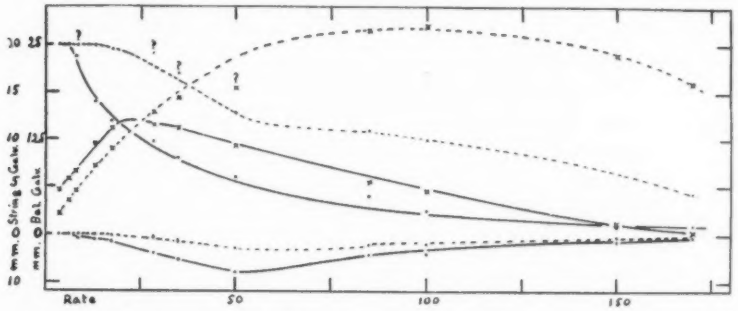


Fig. 19. Curves showing the deflections of the ballistic galvanometer (×) and of the string galvanometer (●), as the rate of interruption is increased while "short-circuiting out the makes." Coil 1, solid lines; coil 2, broken lines.

tion and in accordance with expectation, obtained no deflection. There was no stronger shock at the beginning that might account for the initial contraction. Bernstein, therefore, attributes the initial contraction to some process going on within the tissues.

We have very frequently encountered this phenomenon in the course of experiments in which the gastrocnemius muscle has been stimulated with rapidly repeated shocks from coil 1, with its core in place and without equalizing the makes and breaks. Rarely, if ever, have we seen it when coils 2 and 3 were used in the same way. We are convinced that as we have met the

phenomenon, its cause has been a purely physical one. An initial contraction is obtained, we believe, when the opening of the short-circuiting key during rapid interruption of the primary circuit exposes the muscle to a properly foreshortened make shock.[37] In the case of coil 1, as we have seen, such a make shock may be far more efficient than the full break shock and so may stimulate when the interrupted current from which it is obtained is below the threshold. The initial contraction was rarely seen in the case of coils 2 and 3, because their make shocks are so much lower than the breaks that the foreshortened make rarely, if ever, becomes as efficient as the break. It is easily obtained with coil 1 because the disparity in the amplitude of its shocks is relatively slight. Bernstein encountered it frequently in the course of his experiments undoubtedly because he used "makes and breaks as nearly alike as possible." Either one of such shocks, when properly foreshortened, would undoubtedly be more efficient than the unmodified repeated shocks.

We do not wish to give the impression that this is the only cause of initial contractions. For instance, the initial contractions of the type met with in the introductory experiment of this research, in which *pari passu* with an increase in the rate of interruption a strip of heart muscle contracted less and less frequently until, before it failed entirely to respond, it yielded only an initial contraction, might have a totally different explanation. In such a case the strength of the stimulus is probably reduced by the overlapping of the shocks until it comes to lie just above the threshold. At this stage fatigue or the loss of irritability associated with the so-called introductory contractions might leave only the first stimulus above the threshold value. Other possibilities undoubtedly exist, but this is not the place to enter into a discussion of them.

[37] Another physical explanation of the phenomenon has been offered by Wertheim-Salomonson (29).

SUMMARY

1. This paper embodies the results of a study of the shocks yielded by induction coils of the types commonly used in the laboratory, with a view to the determination of their configuration in relation to their efficiency as stimuli under conditions commonly obtaining in physiological investigations.

2. The deficiencies of the string galvanometer as an indicator of currents of such short duration as induction shocks are discussed, and a rheotome method (the gap method) of making it possible to conveniently determine qualitatively and quantitatively the configuration of shocks with the string galvanometer, is described.

3. A platinum contact key for make shocks is also described.

4. The shocks, both breaks as well as makes, yielded by apparently well-constructed coils, have very different times to maximum and total durations; it is, therefore, not justifiable to speak, without further qualification, of "the duration of the break shock" or "of the make shock." Our quickest break shocks have had about the same time relations as those investigated by Bernstein, for instance, while one of our break shocks lasted about six times as long as Bernstein's. Our make shocks have all lasted considerably longer than Bernstein's make, though the range has been very wide.

5. In general, the briefer the shock the higher must its crest rise if it is to attain to the value of a threshold stimulus for muscle. The briefer threshold shocks contain less current than the slower shocks. The effect of the brevity of a shock in diminishing its value as a stimulus is therefore in part compensated by the steeper potential gradients. The greatest potential difference we have noted between the slowest and quickest of the threshold shocks has been 50 per cent. Usually it is considerably less than this.

6. Threshold break shocks, as well as make shocks, yielded by different coils under the same conditions may contain very different amounts of current.

7. The part of a shock escaping from a short circuit of the secondary coil (a "foreshortened shock") rises higher than the corresponding region of the full shock, and is briefer than the full shock; but if the foreshortening lasts long enough, and especially if the shock is strong, the total process of induction may be greatly prolonged, so that a foreshortened shock may be obtained at a time when the unmodified shock would have been completed.

8. Foreshortening the slower shocks may greatly increase their value as stimuli so that in certain cases a foreshortened make shock may attain a much higher stimulating value than the break shock from the same coil. In such cases the optimum foreshortening falls considerably back of the crest of the unmodified shock. The efficiency of the very quick break shocks cannot be increased by such foreshortening, though it is not decreased until the foreshortening is continued for an appreciable time beyond the crest of the unforeshortened shocks.

9. The physiological efficiency of a shock, aftershortened by short-circuiting the secondary coil, is at no time greater than that of the full shock, and it does not decrease in the case of muscle, at least, until the aftershortening lies somewhere beyond the crest of the shock.

10. Increasing the strength of shocks by approximating the secondary to the primary coil increases their duration, but probably diminishes slightly the potential amplitude of the threshold fraction of the shock. Since the amount of current contained in the threshold fraction is greater in the case of the stronger shocks, it follows that as the coils are approximated the resulting increase in the efficiency of the shock is not quite in direct proportion to the quantity of the contained current.

11. Increasing the secondary resistance diminishes the amplitude of shocks and decreases their time to maximum and their duration; in order to maintain the shocks at the threshold level the coils must be approximated. The amplitude of the threshold shocks possibly decreases slightly, indicating that the steeper gradients determined by the higher resistances more than count-

erbalance the effect of the associated decrease in the quantity of the contained current.

12. In discussing the significance of the foregoing data in relation to the physical calibration of coils, it is shown that only those shocks that can be exactly superimposed (and for this purpose the string galvanometer may be used), can be depended upon to have the same physiological efficiency. Comparative calibrations, based solely upon the quantity of current contained in shocks, can have but little value.

13. From published data as to the duration of induction shocks, it seems clear that at the rate of tetanic stimulation that has at times been employed, overlapping and neutralization of shocks must frequently have occurred. In the case of the coils herein studied overlapping, in the case of equally spaced shocks, theoretically should occur when the break shocks recur at a rate, depending upon the coil, of from 15.7 to 65 per second.

14. By the use of make-break couples it is shown that the break shock is reduced in amplitude and in efficiency when the make-break interval becomes less than the duration of the make shock.

15. When the make-break interval becomes sufficiently short, somewhat shorter than the duration of the break shock, the make shock of threshold couples may rise higher than the break shock; at the same time the make shock may become more efficient physiologically than the break. This has been demonstrated in several ways.

16. The results obtained with break-make couples are in theoretical accordance with the results obtained with single shocks.

17. During tetanic stimulation, increasing the rate of interruption beyond a certain critical rate, which in general agrees with the theoretical considerations, progressively reduces the efficiency of the tetanization as a stimulus. This is due in large part, at least, to physical rather than physiological processes, since the critical rate depends upon the coil employed.

18. When the shocks are overlapping it is impossible to completely short-circuit the make shocks, without at the same time short-circuiting a part of the break shocks.

19. When the rate of interruption does not exceed the critical rate by very much, short-circuiting the make, through the prolongation o the process of induction that may ensue, reduces the efficiency of the break. This effect adds itself to the effect produced by the overlapping of the unmodified shocks.

20. When the rate of interruption is sufficiently high the foreshortened make that results when the attempt is made to short-circuit the make shock may become more efficient physiologically than the break shock.

21. One cause of the "initial contraction" frequently met with when stimulating tetanically, consists in high stimulating efficiency of the foreshortened shock that is apt to occur with the opening of the short-circuiting key that exposes the tissue to the shocks.

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PROTHROMBIN

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By prothrombin is meant the substance contained in blood-plasma and also, as direct experiments show, in blood-platelets, which in the presence of calcium salts is converted to active thrombin. There is a difference of opinion in regard to the factors concerned in this activation. Since calcium salts are present in blood-plasma, together with the prothrombin, and yet, under normal conditions, clotting does not occur, it would appear that either some third factor is necessary for the activation or else the effect of the calcium on the prothrombin is prevented by the presence of a protective substance. Fuld and Spiro,[1] and Morawitz,[2] have adopted the first alternative and have assumed that the third factor is a kinase (thrombokinase of Morawitz, cytozym of Fuld and Spiro), which does not exist in circulating blood but is furnished after shedding by some of the corpuscular elements (platelets). Thrombokinase may be obtained likewise from the tissue-cells in general. Bordet[3] also assumes that the disintegrating platelets furnish an enzyme (cytozyme) that takes part in the formation of the thrombin, but the substance acted upon (serozyme) is not supposed to be present in the circulating blood. The present author has furnished evidence in several researches in support of the second of the alternatives mentioned above. It has been shown that an antithrombin exists in circulating blood in quantities sufficient to bind the prothrombin and thus prevent its activation by the

[1] Fuld and Spiro: Hofmeister's Beiträge, 1904, v, 174.

[2] Morawitz: Hofmeister's Beiträge, 1903, iv, 381, and Deutsches Archiv für klin. medizin, 1904, lxxix, 1 and 215.

[3] Bordet and Delange: Annals de l'Institut Pasteur, 1912, xxvi, 657 and 737.

calcium. Normal circulating plasma is in fact an incoagulable or slowly coagulable liquid, owing to the excess of antithrombin. When blood is shed the platelets in disintegrating furnish a material that neutralizes the antithrombin and permits the calcium to activate the prothrombin. This substance derived from the platelets and furnished also by the other corpuscles of the blood (Austin and Pepper[4]) or the tissue-cells in general comes under the general head of thromboplastic substance. It has been designated by the author, for convenience, as thromboplastin and it has been shown[5] that the essential constituent in this material is a phosphatid which corresponds in its reactions with that member of the group known as kephalin. In shed blood the platelets furnish both thromboplastin and prothrombin. Their disintegration therefore exerts a double influence in hastening the process of clotting; in the first place by furnishing a supply of thromboplastin which neutralizes the antithrombin and thus disturbs the equilibrium existing in the blood between the prothrombin and antithrombin, and secondly by yielding an additional supply of prothrombin which displaces the equilibrium in the same direction. The main object of the present paper is to support the view that calcium salts alone are concerned in the activation of prothrombin to thrombin, and that there is no necessity for assuming the participation of a hypothetical kinase in this process.

THE SEPARATION OF PROTHROMBIN FROM BLOOD-PLASMA

To demonstrate the correctness of the view just stated it is necessary to isolate the prothrombin from the other fibrin factors found in the blood-plasma. The efforts made to effect this separation have been successful in part an least. The method finally adopted was the following: Blood taken from the carotid was oxalated in the usual manner (1 part of a 1 per cent solution of sodium oxalate, made up in 0.9 per cent solution of sodium chloride, to 8 or 9 parts of blood). The mixture was centri-

[4] Austin and Pepper: Archives of Internal Medicine, 1913, xi, 305.
[5] Howell: American Journal of Physiology, 1912, xxxi, 1.

fugalized to obtain a clear plasma. The plasma was sucked off, and, in small portions of 4 to 6 cc., was precipitated by the addition of an equal volume of acetone. The precipitate was thrown at once on a filter and filtration effected quickly by an air-pump. As soon as the liquid had run through, the filter was filled with ether which was also sucked through rapidly. The gelatinous precipitate was spread thin upon the paper and dried rapidly in the current of air from an electric fan. This dried material was kept until needed in a desiccator. The prothrombin was obtained from the dried precipitate by extracting it with water to which a trace of sodium bicarbonate was added. Extraction was made for one-half to one hour and the solution was then filtered. The filtrate was usually opalescent. The presence of prothrombin in this solution was demonstrated easily by the reaction with fibrinogen and calcium solutions, according to the following example:

Fibrinogen drops	*$CaCl_2$ (0.5 per cent) drops*	*Prothrombin drops*	*Coagulation Time*
10	**2**		No clot in 24 hours
10		5	No clot in 24 hours
10	2	5	Solid clot in 4 minutes

Occasionally the extract of prothrombin gave a feeble clot after many hours upon the addition of calcium solution, indicating that a small amount of fibrinogen had passed into solution, but in the great majority of the extracts made this reaction did not occur. The only variation from the example cited above lay in the rapidity with which the calcium prothrombin solution caused the fibrinogen to clot. The time necessary for the clotting showed considerable irregularity in the earlier experiments, owing, it is believed, to the tendency of the acetone to render the prothrombin insoluble. In the later experiments in which the acetone was removed as quickly as possible after precipitation, by suction and by washing once with ether, the reaction was much more regular. It is evident that the extracts of the dried precipitate contained a prothrombin material, and for its conversion to active thrombin the presence of a calcium salt was all that was required. There is however one objection to the validity of

this conclusion which must be considered. Assuming that a third factor, a kinase, is concerned in the reaction, and assuming also that this kinase was present in the oxalated plasma, it is possible that it may have been precipitated by the acetone and been redissolved in the extract made from the dried precipitate. As far as the author is aware there is no accepted test for the presence of this kinase other than the existence of thrombin, unless it be admitted that the kinase of Morawitz is identical with thromboplastin, that is, with the substance in tissue-extracts which facilitates or initiates clotting. Tissue extracts, or the kephalin obtained from them, are characterized by their power to cause clotting in peptone-plasmas, and this reaction was used therefore upon the extracts of prothrombin to ascertain whether they contained thromboplastic material. A peptone plasma was chosen which did not clot spontaneously even when diluted with an equal volume of water. Addition of tissue extracts or kephalin solution caused clotting, but the prothrombin extracts were without effect. It may be said therefore that these extracts were lacking in any effective amount of thromboplastic material. In the earlier experiments with the prothrombin extracts it was noted that addition of kephalin solution to the calcium-prothrombin mixture often hastened greatly its action upon fibrinogen. In the later experiments in which the method of quick filtration and washing with ether was used this facilitating action of the kephalin was much reduced or was lacking entirely. From the author's point of view this facilitating effect of kephalin would indicate that some antithrombin was present at times in the solutions of prothrombin, particularly in the earlier experiments Direct examination of the extracts made in several cases bore out this explanation.

The prothrombin extract was heated first to 60°C. to destroy or weaken the prothrombin and its effect was then tested upon known mixtures of thrombin and fibrinogen in comparison with controls, according to the following schema.

Heated Prothrombin Extract drop	*Thrombin drops*	*Time Interval hour*	*Fibrinogen drops*	*Coagulation Time*
1	1	1	10	1½ to 2½ hours
1	2	1	10	40 minutes
1	4	1	10	30 minutes
Control with water drop				
1	1	1	10	50 minutes
1	1	1	10	25 minutes
1	1	1	10	20 minutes

Several experiments of this kind gave similar results.

In the method of preparation used for the prothrombin we must believe that more or less of the antithrombin contained in the blood-plasma may appear in the final extract. When the amount of antithrombin present is at all noticeable the use of kephalin facilitates the clotting effect of the calcium prothrombin mixture. In preparations in which the amount of antithrombin is reduced or absent the calcium prothrombin mixture clots the fibrinogen promptly and its effect is increased but little if any by the addition of kephalin solutions.

The prothrombin extracts obtained by the method described were quite stable. When left at ordinary temperatures they maintained their efficiency for long periods, usually in fact until some signs of putrefactive changes were apparent. Heated to 60°C. their activity was markedly diminished but not wholly destroyed. It was found that these prothrombin extracts might be reprecipitated one or more times with acetone, but in each successive precipitate the amount of prothrombin present was reduced, so that the use of this method for the further purification of the prothrombin was abandoned.

THE PRESENCE OF PROTHROMBIN AND THROMBOPLASTIN IN BLOOD-PLATELETS

Occasion was taken during these experiments to verify the reports of other observers regarding the presence of prothrombin and of thromboplastin (Morawitz, Bayne—Jones) in the blood-platelets. The platelets were obtained in the usual way by differential centrifugalization and were washed carefully in a

large volume of saline solution (0.9 per cent sodium chloride). They were then extracted with water to which a trace of sodium bicarbonate was added (5 drops of a half per cent solution to 10 cc. of water). The extract thus made had no coagulating effect at all upon a solution of fibrinogen when used alone, but together with calcium chloride caused clotting in a short time. Example:

Fibrinogen, 10 drops + Plate extract 5 drops gave no clot in 24 hours.
Fibrinogen, 10 drops + Plate extract 5 drops, + $CaCl_2$ (0.5 per cent) 2 drops gave clot in 20 minutes.

The platelets therefore either contain prothrombin within their cytoplasm or else they carry this material down from the plasma in some sort of adsorptive combination. The first alternative would seem to be much more probable.

The presence of thromboplastin in the platelet extract was demonstrated by its reaction with peptone plasma. Example:

Peptone plasma 10 drops + Platelet extract 10 drops + water 10 drops gave clot in 1 hour.
Peptone plasma 10 drops + water 20 drops gave no clot in 24 hours.
Peptone plasma 10 drops + water 10 drops + prothrombin extract 10 drops gave no clot in 24 hours.

The difference between the platelet extract and the prothrombin extract in regard to thromboplastic substance is brought out clearly in tests of this kind.

THE EFFECT OF BARIUM, STRONTIUM AND MAGNESIUM SALTS UPON PROTHROMBIN

Since by the method described above prothrombin was obtained separated more or less completely from the other fibrin factors, it seemed to be a suitable opportunity to determine whether barium, strontium and magnesium share with calcium the property of activating prothrombin to thrombin. A single experiment upon this point seemed to be sufficiently decisive. One-half per cent solutions were made of calcium chloride, calcium nitrate, strontium chloride, magnesium chloride and barium chloride and their action was tested upon mixtures of fibrinogen and prothrombin extract. The result was as follows:

Fibrinogen 10 drops + Prothrombin extract 5 drops gave no clot in 24 hours.

Fibrinogen 10 drops + Prothrombin extract 5 drops + calcium chloride 2 drops gave clot in 10 minutes.

Fibrinogen 10 drops + Prothrombin extract 5 drops + calcium nitrate 2 drops gave clot in 15 minutes.

Fibrinogen 10 drops + Prothrombin extract 5 drops + strontium chloride 2 drops gave no clot in 6 hours, but partial floating clot between 6 and 20 hours.

Fibrinogen 10 drops + Prothrombin extract 5 drops + magnesium chloride 2 drops gave no clot in 6 hours, but feeble floating clot between 6 and 20 hours.

Fibrinogen 10 drops + Prothrombin extract 5 drops + barium chloride 2 drops gave no clot in 24 hours.

PROTHROMBIN IN THE BLOOD-PLASMA

After the blood is shed the disintegration of the blood-platelets yields no doubt a supply of thromboplastin and prothrombin. Presumably also during the normal circulation these elements undergo dissolution of a more gradual character and we should expect therefore to find both substances among the constant constituents of the circulating blood. To demonstrate that this is actually the case is difficult or impossible with the methods at our disposal at present. By centrifugalization or by filtration through a Berkefeld filter one may remove all corpuscular elements from the blood, but it remains possible of course that some of the platelets may undergo disintegration during this process and thereby furnish to the plasma certain materials not present normally in the circulating blood. As far as the author can see this possible error can not be excluded. One can only use every known precaution to keep the corpuscles intact. Both of the methods suggested above have been attempted with blood-plasma as well as lymph-plasma and the results, as far as they go, indicate the presence of both prothrombin and thromboplastin in the plasma of the circulating blood and lymph, although in the lymph the thromboplastin at least is in much smaller concentration than in the blood. In the experiments with centrifugalized plasma the procedure used was as follows:

The fasting animal was bled from the carotid through a vaselined canula into a paraffined centrifugal tube containing sufficient sodium oxalate (made up in 0.9 per cent solution of sodium chloride) to give a final mixture of 0.1 per cent sodium oxalate. Only the first sample (40 cc.) collected was used. As soon as the tube was filled the contents were mixed by pouring carefully into a second paraffined centrifugal tube. This latter tube was then centrifugalized at half speed (1500 to 2000 revolutions) for 20 minutes. The supernatant plasma was pipetted off through a vaselined tube, a portion was kept for examination and the remainder was centrifugalized for one hour at full speed (3000 revolutions). Two specimens of plasma were thus obtained, one completely centrifugalized, very clear and presumably free from all formed elements; the other incompletely centrifugalized and containing still many platelets in suspension When these two specimens were recalcified, if the expression may be used, by the addition of optimum amounts of calcium chloride, it was found that the completely centrifugalized plasma required a longer time to clot. The difference however was not very great. In the most successful experiment the incompletely centrifugalized plasma clotted in 10 minutes, the other in 30 to 35 minutes. In lymph a much greater difference was observed in most cases. The following records were obtained:

	Incompletely centrifugalized	*Completely Centrifugalized*
March 3, 1914	13 minutes	No clot in 3 hours
March 8, 1914	30 "	Clot between 2 and 20 hours
March 17, 1914	15 "	20 to 25 minutes
March 21, 1914		No clot in 20 hours
March 24, 1914	30 to 40 "	Between 5 and 20 hours
March 27, 1914	25 "	Between 3 and 15 hours

The results with lymph-plasma were variable, but in general the complete centrifugalization greatly prolonged the time of clotting after the addition of calcium. That this delay was due to a deficiency of thromboplastin rather than of prothrombin was indicated by the fact that the addition of a kephalin-solution (tissue extract) to the completely centrifugalized plasma, together with the calcium, was followed by prompt clotting within a

few minutes (4 to 30). The experiments upon blood-plasma passed through a Berkefeld filter are described by Goddard in a separate paper[6] and may be referred to very briefly. Using all possible precautions in regard to vaselining or paraffining the tubes it was found that the first portion of the filtrate collected might fail to clot even with thrombin, indicating therefore that the fibrinogen had been strained off. In intermediate portions the addition of calcium alone might be insufficient to cause clotting while calcium plus tissue-extract (kephalin) was effective. In these portions therefore prothrombin was present while thromboplastin was lacking or was present in ineffective amounts. In the last portions of the filtrate calcium chloride alone caused clotting as in the unfiltered plasma, although the time required was usually much longer. As far as these experiments go therefore they support the conclusion that prothrombin and thromboplastin, in variable amounts, are constantly present in the circulating plasma.

SUMMARY

1. Prothrombin may be precipitated by acetone from oxalated blood-plasma and be obtained in solution free from the other fibrin factors, with the possible exception of traces of antithrombin.

2. The prothrombin is converted to active thrombin in the presence of calcium salts. No third factor seems to be necessary for this activating process.

3. The activating property of calcium salts is exhibited to a much less extent by strontium salts, and very feebly by magnesium salts.

4. The prothrombin in salt free or salt poor solutions is weakened but not destroyed by heating to 60°C.

5. Aqueous extracts of the blood-platelets show the presence of both prothrombin and thromboplastin.

6. Prothrombin (probably some thromboplastin also) is contained in the plasma of circulating blood. In shed blood disintegration of the platelets furnishes an additional supply of prothrombin and thromboplastin.

[6] Goddard: American Journal of Physiology, 1914, xxxv.

THE COAGULATION OF LYMPH

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The lymph used in these experiments was obtained from dogs by placing a canula, vaselined along its inner surface, into the thoracic duct. The animals were anesthetized with morphia and ether. The flow from the canula was variable, but in fed animals with a milky lymph was quite abundant, averaging about 0.5 cc. to a minute.

EFFECT OF TISSUE-EXTRACT (KEPHALIN-SOLUTION) UPON THE TIME OF COAGULATION

It is usually stated that lymph coagulates more slowly than blood and gives a feebler clot. According to the results of these experiments, eight in number, the time of coagulation varies greatly under different conditions. In animals starved for 48 hours whose lymph showed but little evidence of chyle-fat, clotting took place in 10 to 20 minutes after the sample (1 cc.) had been collected. On the other hand the more abundant milky lymph collected from fed animals clotted more slowly, requiring from 30 to 60 minutes for the specimens first collected, and as much as 1 to 3 hours for specimens caught after an hour or two, although at this time microscopic examination showed usually a great increase in the number of lymphocytes. While the pure lymph uncontaminated by mixture with the tissue juices clots more or less imperfectly, compared with mammalian blood, it coagulates promptly and firmly if tissue extract is added to it.[1] In this series of experiments instead of employing a tissue extract use was made of the phosphatid material (kephalin) which I

[1] My attention was called to this fact by Dr. E. L. Opie.

have described previously[2] as forming the essential constituent of tissue extracts, so far as their effect on coagulation is concerned. Specimens of pure lymph mixed with equal volumes of an aqueous solution of kephalin clot solidly in from 5 to 7 minutes, indicating that the amounts of fibrinogen and thrombin present are adequate for prompt coagulation. The explanation of the imperfect clotting of the lymph is to be found therefore in the lack of thromboplastic material. According to my views this material, liberated from the tissue-cells in general, plays the rôle of neutralizing the antithrombin present in the plasma. In the lymph, as in the avian blood, the absence of easily destroyed elements, such as the blood-platelets, which furnish thromboplastin, accounts for the imperfect clotting. In the lymph there is a relative excess of antithrombin, as there is in the plasma of the circulating blood, which protects it from clotting. The new thromboplastic material that is added to the lymph after shedding must come from the lymphocytes and apparently these elements disintegrate more slowly than the mammalian blood-platelets. That this view is correct is indicated by an experiment of this kind:

Experiment, March 31, 1914. Large dog, recently fed. Lymph collected from the thoracic duct, very milky and clots very slowly. Some of the unclotted lymph was centrifugalized at high speed. The upper portion of the centrifugalized plasma was removed and had not clotted in 8 hours, although found clotted at the end of 24 hours. The portion of the lymph left in the centrifugal tube in contact with the sedimented corpuscles clotted on the contrary in 1 hour or less, owing probably to thromboplastic material yielded by the corpuscles. The supernatant plasma which had not clotted in 8 hours gave a firm clot in 3 minutes when kephalin solution was added.

THE PRESENCE OF ANTITHROMBIN

That antithrombin is present in the lymph in amounts equal substantially to that in the blood-plasma may be shown readily by such an experiment as the following:

[2] Howell: American Journal of Physiology, 1912, xxxi, 1.

Experiment, March 31, 1914. Lymph collected from the thoracic duct of dog—lymph milky, clots slowly (50 to 60 minutes). Specimen of lymph collected in oxalate solution (8 cc. of lymph to 1 cc. of a 1 per cent solution of sodium oxalate made up in 0.9 per cent solution of sodium chloride). Immediately afterwards a similar specimen of blood was taken from the carotid into oxalate solution, using the same proportions. The two specimens were centrifugalized for 40 minutes, and a portion of the lymph plasma was further centrifugalized for 1 hour. The three specimens of plasma thus obtained were then heated to 60°C. to precipitate the fibrinogen and to destroy the prothrombin. The antithrombin in the heated plasmas was tested in the usual way upon mixtures of thrombin and fibrinogen (dried plasma). The concentration of these latter solutions was such that four drops of the thrombin added to ten drops of the fibrinogen caused clotting in 3 to 4 minutes.

Thrombin solution drops	*Heated blood-plasma drop*	*Time interval mins.*	*Fibrinogen solution drops*	*Coagulation time*
2	1	15	10	No clot
3	1	15	10	2 hours 10 minutes.
4	1	15	10	20 minutes.
5	1	15	10	10 minutes.

Thrombin solution drops	*Heated lymph plasma centrifugalized 20 mins. drop*	*Time interval mins.*	*Fibrinogen solution drops*	*Coagulation time*
2	1	15	10	No clot
3	1	15	10	2 hours 10 minutes.
4	1	15	10	15 to 20 minutes.
5	1	15	10	10 minutes.

Thrombin solution drops	*Heated lymph plasma centrifugalized 1 hr. 20 mins. drop*	*Time interval mins.*	*Fibrinogen solution drops*	*Coagulation time*
2	1	15	10	No clot
3	1	15	10	2 hours 10 minutes.
4	1	15	10	20 minutes.
5	1	15	10	10 minutes.

According to this experiment the lymph plasma, freed from corpuscles by centrifugalization, contains the same amount of antithrombin as the blood-plasma of the same animal.

THE ABSENCE OF BLOOD-PLATELETS

Those who have investigated the microscopical structure of lymph either make no mention of platelets or deny specifically their existence.[3] In this series of experiments I have frequently made examinations for platelets either upon the fresh lymph as it flowed from the canula, or in the oxalated lymph, but without success. In the latter I have also examined the corpuscular sediment obtained by centrifugalization, but neither in the deposit from a first nor in that of a second centrifugalization have I been able to find platelets, although by this method, as applied to blood-plasma, these structures are obtained in great abundance.

It would seem quite certain therefore that platelets do not constitute a normal element in the lymph.

In the clotting of blood the platelets play an important part by liberating an additional supply of thromboplastic substance and of prothrombin. It is a matter of interest to inquire whether the characteristic element of the lymph, the lymphocyte, is capable also of supplying the same material. In order to answer this question I have resorted to differential centrifugalization of the lymph with subsequent extraction of the deposits. The results are described in the next paragraph.

DIFFERENTIAL CENTRIFUGALIZATION OF THE LYMPH

The procedure used in these experiments was as follows: The lymph as it flowed from the canula in the thoracic duct was caught in an oxalate solution so that the final mixture contained 0.1 per cent sodium oxalate, or, in some experiments, in a solution of hirudin in sodium chloride (0.9 per cent) of sufficient strength to prevent the coagulation of the lymph. These solutions were then centrifugalized for 10 to 30 minutes at half-speed (1500 to 2000 revolutions). The supernatant plasma was drained off. The centrifugal tube was filled with oxalated saline and the sediment was stirred up in this solution by means of a glass rod.

[3] Vinci and Chistoni: Archives italiennes de biologie, 1910, liii, 206.

This mixture was centrifugalized and the sediment was again treated with the same oxalated saline and centrifugalized. After this final centrifugalization the supernatant wash liquid was drained off and the sediment was extracted with water, containing a trace of sodium bicarbonate. This solution was designated as *Extract of Deposit I*. In the case of the hirudinized lymph the wash liquid was in some case a hirudinized saline solution instead of an oxalated saline solution. The supernatant lymph-plasma from the first centrifugalization was again centrifugalized at full speed (3000 revolutions) for 1 hour to 1 hour and 30 minutes. The liquid was then drained off and the minute residue was in some cases washed once with the oxalated saline and then extracted with water containing a trace of sodium bicarbonate. In other cases the extract was made without this previous washing, owing to the almost invisible character of the sediment. The final solution in this case was designated as *Extract of Deposit II*. Deposit I contained the mass of the cells present in the lymph, chiefly of course lymphocytes, together with the precipitated calcium oxalate in the oxalated specimens, and the aqueous extracts of this deposit showed in all cases a strong thromboplastic action. The presence of thromboplastin was determined by the effect of the extract upon thoroughly centrifugalized oxalated lymph. The supernatant plasma of oxalated lymph after centrifugalization for 1 hour or more clots very slowly or not at all when a calcium solution is added. But when a solution of kephalin or of the extract of Deposit I is added together with calcium clotting takes place very promptly, as may be illustrated by the following example.

Oxalated and also hirudinized specimens of lymph were centrifugalized for 1 hour and 30 minutes. The supernatant plasma gave no clot in 20 hours with calcium solution alone. With calcium plus kephalin-solution clotting occurred in 5 to 8 minutes. With calcium plus Extract of Deposit I clotting took place also in 5 to 8 minutes, in both the oxalated and the hirudinized specimens. With calcium and Extract of Deposit II clotting occurred in 20 to 25 minutes. Similar results were obtained in all cases

and there can be no doubt that aqueous solutions of the corpuscles found in the lymph yield a thromboplastic material similar to that obtained from the blood-platelets.

The corpuscles contained in the lymph consist mainly of small lymphocytes[4] (90 to 100 per cent) with varying numbers of large mononuclear lymphocytes and of red corpuscles. It is permissible to assume that the thromboplastic material present in the extracts of the deposits was derived from the small lymphocytes. As shown by the experiment referred to on p. 484 these lymphocytes, even in the shed lymph, disintegrate slowly. Whether or not these corpuscles undergo disintegration, with liberation of thromboplastin, in the circulating lymph, can not be determined. Examination of various lymphs by the method of centrifugalization and also by the method of filtration,[5] indicates that in some lymphs, at any rate, thromboplastic material is present in solution in the circulating lymph, but the amount is small and variable. When the lymph is shed a new supply of this material is not added so promptly as in the case of the blood, since the lymphocytes are more stable structures than the platelets. Hence, the slower clotting of the lymph. As stated above addition of thromboplastic material (tissue-extract, or kephalin) makes the lymph clot as promptly and as firmly as the blood.

PROTHROMBIN

Evidence has been furnished that the blood-platelets yield on dissolution prothrombin as well as thromboplastin. It is important to ascertain whether the lymphocytes of the lymph likewise serve as a source of prothrombin. The experiments undertaken to answer this question were made with the Extracts of Deposits I and II described above. These extracts were tested with and without the addition of calcium solutions upon solutions of fibrinogen prepared from dog's or cat's blood. The

[4] Rous: Journal of Experimental Medicine, 1908, x, 537; Biedl and v. Decastello: Pflüger's Archiv, 1901, lxxxvi, 259; Davis and Carlson: American Journal of Physiology, 1909, xxv, 173.

[5] Goddard: American Journal of Physiology, 1914, xxxv, 333.

results of these experiments were not wholly consistent. Deposit I, containing the mass of the lymphocytes, when obtained in the oxalated solutions and washed twice, as described, showed distinct evidence of containing prothrombin or thrombin. The extract of this deposit added to fibrinogen solutions together with calcium always caused clotting. When the extract was added without the calcium no clotting occurred in some specimens, while in others coagulation of the fibrinogen took place after a number of hours. This latter reaction indicated the presence of active thrombin present as such in the deposit of corpuscles or formed in some way from prothrombin during the process of preparation of the extract.

The apparent conclusion to be derived from these experiments was that in the deposit of corpuscles from the oxalated lymph thrombin is found in either active or inactive (prothrombin) form. It is a question however whether this material is contained in the cytoplasm of the corpuscles or is simply carried down from the plasma by adsorptive combination with the corpuscles and the precipitate of calcium oxalate. The fact that Deposit I was twice washed with large volumes of saline before being extracted would seem to make the latter suggestion improbable. But control experiments showed that the prothrombin from lymph or blood carried down by a precipitate of calcium oxalate is not removed readily by washing the precipitate. It was found moreover that the Extracts of Deposit I obtained from hirudinized lymph although rich in thromboplastic material failed to show any indication of the presence of prothrombin. The results on the whole, as regards the presence or absence of prothrombin in the lymphocytes, were not clear, but in view of the negative finding with the washed corpuscles from the hirudinized lymph and the possibility that in the deposit from the oxalated lymph the prothrombin obtained was simply adherent to the precipitate of calcium oxalate, the conservative conclusion would seem to be that it is doubtful whether the lymphocytes contain prothrombin, although like the platelets and the tissue-cells in general they contain thromboplastic material.

Prothrombin in solution in the plasma

A further question of interest is whether or not prothrombin exists in solution in the lymph plasma. To this question the experiments gave a clear and satisfactory answer. The oxalated plasma after thorough centrifugalization for one hour and a half at high speed (3000) may clot very slowly or not at all when calcium solutions are added in proper amount, owing, as has been explained to the absence or small amount of thromboplastin and the relative excess, therefore, of antithrombin. But if to such plasmas there is added an appropriate amount of thromboplastic substance, in my experiments solutions of kephalin were used, clotting occurs in a few minutes. This result indicates that prothrombin is present in solution in the plasma. A similar result was obtained with oxalated lymph plasma filtered through a Berkefeld filter.

Only one experiment of this latter kind was made. Fourteen cubic centimeters of lymph after mixture with oxalate solution were filtered through a dry Berkefeld filter and the filtrate was divided into two parts, part *a*, which came through first, and part *b*, the last portion of the filtrate. The lymph before filtration gave a clot with calcium alone in 80 minutes and with calcium plus kephalin in 8 minutes. Portion *a* gave no clot with calcium alone, none with calcium plus kephalin, and none with calcium plus a boiled extract of fresh brain. Addition of thrombin gave a very feeble clot, so that in this filtrate very little fibrinogen was present and apparently no prothrombin or thromboplastin. In the second filtrate (part *b*) no clotting occurred with calcium solutions alone while with calcium plus kephalin or the boiled brain extract clotting took place in from 5 to 8 minutes. In this filtrate therefore prothrombin and fibrinogen were present but thromboplastin was lacking or if present was in amounts insufficient to neutralize the antithrombin. The Berketeld filter may be supposed to strain off all formed elements or fragments, and the fact that the second portion of the filtrate clots readily when calcium and thromboplastic substance are added is evidence for the view that the prothrombin in the filtrate exists in solution in the circulating lymph plasma.

SUMMARY

1. The coagulation-time of lymph varies greatly. In well-fed animals with much chyle-fat in the lymph coagulation is slower than in the clear lymph from fasting animals.

2. Addition of thromboplastic material (tissue-extract or kephalin solutions) causes the lymph to clot promptly and firmly.

3. Lymph plasma contains antithrombin in the same concentration as in blood-plasma. When freed from corpuscles by long centrifugalization the lymph plasma clots with great slowness, owing to a relative excess of antithrombin. Addition of kephalin solution to such plasmas causes prompt clotting.

4. The thromboplastin in solution in lymph-plasma is less in amount than in the blood-plasma. In shed lymph a new supply of thromboplastin is furnished by the lymphocytes, but more slowly than in the case of the blood in which the additional thromboplastin is derived from the unstable platelets.

5. Prothrombin is present in solution in the circulating lymph. Its activation to thrombin by calcium is retarded or prevented by the relative excess of antithrombin.